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A STUDY OF AN
ADVANCED CONFINED LINEAR ENERGY SOURCE

By M. C. Anderson and W. B. Heidemann

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Explosive Technology
Fairfield, California 94533

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SUMMARY

Under Contract NAS1-9984 with the National Aeronautics and Space Administration, Langley Research Center, Explosive Technology has performed a literature survey and a test program to develop and evaluate an Advanced Confined Linear Energy Source. The Advanced Confined Linear Energy Source is an explosive or pyrotechnic X-Cord (mild detonating fuse) supported inside a confining tube capable of being hermetically sealed and retaining all products of combustion. The energy released by initiation of the X-Cord is transmitted through the support material to the walls of the confining tube causing an appreciable change in cross sectional configuration and expansion of the tube.

When located in an assembly that can accept and use the energy of the tube expansion, useful work is accomplished through fracture of a structure, movement of a load, reposition of a pin, release of a restraint, or similar action. The tube assembly imparts that energy without release of debris or gases from the device itself. This facet of the function is important to the protection of men or equipment located in close proximity to the system during the time of function.

The program began with a literature survey that led to selection of 2024-0 and 2024-T3 aluminum and 304, 17-7 PH and 347 stainless steel tube materials. The selected tube diameter was 3/8-inch, with wall thicknesses of 0.028-, 0.035- and 0.065-inch. Two explosives were selected: HNS and HNS/Ti/$KClO_4$ (STA) mixture (ET's "Flashcord"). These support materials were selected: fiberglass, silicone rubber and lead (Pb).

A series of tests was then conducted to determine the most promising explosive, support and tube material combination. The most promising combination of materials using 3/8-inch-diameter tube was: 304 stainless steel, 0.065-inch wall thickness, STA explosive with maximum core load of 18 gr/ft, lead (Pb) support. Test results and conclusions are presented as baseline information for the design of future systems for specific end-use applications.

INTRODUCTION

The need for a "clean" actuation system for a wide variety of applications, such as aircraft, satellites and spacecraft, whether manned or unmanned, is becoming increasingly prevalent. As these missions and vehicles become more sophisticated, the requirement for a system that can perform a function, uniquely suited to an explosive system, without contaminating the immediate environment or transferring more shock into the surrounding structure than necessary to accomplish the function becomes more stringent.

Explosive Technology has an extensive background in development and fabrication of this type of a system. Expanding shielded mild detonating cord (X-SMDC), or "expanding tube," assemblies have been fabricated and tested for use in a variety of applications such as:

(1) Separation of joints

(2) Breaking of bolts

(3) Actuation of components

Appendix A describes the concept as used in the F-14 canopy removal system. Appendix B describes the concept as applied to a separation system wherein the energy release is used to effect a structural separation and impart a velocity between the separated sections. Typical results of other in-house programs are included in Appendix C.

Those systems were all designed and qualified in accordance with a specification defining a singular objective in a specific system application. It was the purpose of this study, then, to investigate the basic expanding tube concept and define the various functional characteristics of the concept as certain parameters were varied. The resultant data would then provide designers with baseline information from which they could incorporate the appropriate design parameters into any end-use application.

DESCRIPTION OF APPARATUS

Expanding Tube Assembly

The expanding tube assembly consists of a length of metal tubing housing a length of X-Cord, which is supported by a material within the tube. The tube subassembly is fitted with end boosters and is hermetically sealed and fitted with appropriate hardware for mating with threaded connectors or other devices. The tube assembly is then formed to a flattened cross section and configuration necessary to meet the end-use application. In the case of this test program, the working section is flattened to fit an adaptor to the energy measuring apparatus.

A list of the tubing materials and sizes, X-Cord types and sizes, and support materials tested is given in Table I.

Test Instrumentation

The objective of the program was to evaluate the effect of varying the parameters of the X-SMDC assembly. By measuring the amount of work done by the expanding tube, an evaluation can be made. This measurement is made by installing the test specimen (X-SMDC) in a fixture that is adapted to an "energy sensor." The work accomplished when the assembly is functioned is measured by the amount of deformation sustained by a piece of calibrated honeycomb installed in the energy sensor. The energy sensor operation at Explosive Technology is described in Appendix D and References 1 and 2.

Figure 1 illustrates the basic test assembly. Figures 2, 3 and 4 depict the thermal conditioning setups used during extreme temperature testing. A Despatch Style V-29SD 20 kW high temperature chamber was used to condition the high temperature test assemblies by forced convection. Copper constantan thermocouples were used in conjunction with Leeds & Northrup (L&N) potentiometers to measure specimen temperatures. Low temperature firings were performed in a specially constructed cryogenic cooling shroud utilizing liquid nitrogen (LN_2) as an expendable refrigerant. The restrained flat was cooled conductively by mounting the specimen holder in an LN_2-cooled heat-sink block. The unrestrained flats, and the remainder of the specimen, were cooled by radiation and convection in a black-body thermal shroud, also chilled by LN_2 (see Figure 2.) Surface-bonded thermocouples were used with L&N potentiometers to measure temperature. In both high and low temperature tests, the barrel of the energy sensor and the Honeycomb were protected from temperature extremes.

Minimum and maximum temperature capabilities were -320°F to +850°F. Thermal stabilization at the specified test temperature was reached in approximately 20 minutes.

PROCEDURE

Literature Survey

The objective of the literature survey was to ascertain what work of a similar nature may have been accomplished, and to investigate and evaluate materials that would have advantages for this particular application. The literature was surveyed in a general manner to assure that all the latest information was available for this program. References 3 through 24 were reviewed only for guidance during the program and do not specifically apply to the end purpose of the work reported herein.

The survey for the confinement structure was primarily oriented toward, and purposely limited to, metallic tubes. It is believed that, within the state of the art, better techniques for affixing end fittings, more reliable sealing and higher structural integrity are available with metal than with other materials. It is also believed that metallic confinement is the best approach to obtain a minimum envelope. The physical characteristics of metals suitable for the dynamic forces expected were reviewed and the most potentially attractive materials selected for further evaluation. The availability of the material in a tubing configuration was then ascertained for the practical aspects of inclusion into the test program.

The other area of interest involved in the literature survey was chemical energy source. It was expected that the characteristic of the energy release or application would have an effect on the total system response or function. During the literature survey, various core materials were considered. The data from testing previously accomplished was reviewed for an evaluation of this parameter.

The support material was also an important facet of the energy system and potential materials were screened for use in the test program. Additionally, historical test data were reviewed for applicability.

Support material was surveyed primarily for its support capabilities under the expected environments, rather than for its ability to transmit energy.

Tube Assembly Evaluation

A test and evaluation program was designed to test the materials and combinations studied during the literature survey which would seem to lend themselves to the most efficient, practical expanding tube system. Because the system is a complex interrelationship between the strength, density and energy release characteristics of a variety of materials and the geometry and dynamic response thereof, it appeared to be most practical to test the various combinations and measure and evaluate the results.

A matrix of probable combinations was devised for the initial portion of the program. Various combinations were selected for test early in the program

to ascertain gross capabilities. A material combination was assembled with a predetermined quantity of pyrotechnic or explosive per unit length (expressed as core load in grains per foot of core material). The assemblies were tested, the energy output measured and, providing the tubing did not split, the next higher increment of core load was tested.

The underlying goal was to achieve as much performance from a given combination as possible and still ensure the structural integrity of the assembly after functioning. The performance was measured as energy transmitted to the energy sensor. The structural integrity was evaluated by visual inspection of the post-fired tube. It was either split or not (a "Go" or "No-Go" result).

Because the nature of this type of testing is time consuming, i.e., the subsequent test configuration depends upon the result of the previous test, some assemblies were assembled before testing was complete on previous or deciding tests. As the testing progressed, the materials and tube sizes that appeared to offer the best potential for an efficient system were more extensively tested to develop data to define the characteristics of the "best" system. Because of the large number of possible combinations, many combinations were eliminated by early results and therefore not tested.

As the best combination evolved by evaluation of test results, the capability of that combination to function at high and low temperature was measured. With all test results in, the best combination of tube material and core load was the one that provided the greatest expansion without rupture of the tube.

The most promising combination of materials was selected to evaluate what change in energy could be expected at +300°F and -300°F and the effect on structural integrity. Assemblies were stabilized for 1 hour before functioning.

Movement of the tube wall as it was functioned was also of great interest. A high-speed (streak) photographic record of this phenomenon was made.

RESULTS

Literature Survey

A significantly large and diverse body of technical literature was screened during this program (as delineated in the References). Those publications with merit were further reviewed in detail to determine those factors most important to the development of an optimum linear energy source (expanding tube) system.

A review of expansion mechanisms indicated that there were essentially two categories of considerations: metallurgical (local) and structural (tube responds as a pressure vessel). In review of both considerations, a face centered cubic (FCC) metallurgical lattice appeared to be optimum, in that certain FCC matrix alloys, notably the austenitic steels, demonstrated increased tensile and yield strengths and greater ductility at high strain rates. Further, austenitic steels were susceptible to strain hardening, which enhanced the uniformity of radial expansion of the tube under optimum conditions.

In consideration of the hydrodynamic impulse to be imparted to the wall of the tube to effect optimum energy transfer, a review of theorized data indicated that a rectangular impulse, in which the magnitude of the "effective load" (peak impulse divided by twice the mean time of the pulse) slightly exceeded the dynamic yield strength of the metal, should approach the optimum impulse for nonrupturing expansion of thin-wall tubes. It was further seen that this preferred impulse may be accomplished by the use of either a conventional high-explosive-loaded detonating cord jacketed with an attenuating media, with a detonating cord loaded with a less brisant detonating compound, or by a combination of the two.

After an extensive review of static and dynamic physical characteristics of about 100 metals (data on 55 listed in Table II), and in further consideration of data previously obtained from tests conducted by ET on other programs, seven candidate metals were chosen. In consideration of maximum ET data utilization, a tube diameter of 3/8-inch was chosen as standard. Similarly, previous ET data indicated that tube wall thicknesses of 0.035- and 0.065-inch were satisfactory choices to fully investigate the practical range of energy output.

An attempt was therefore made to find procurement sources for best available alloys in the two wall thicknesses of the 3/8-inch diameter tube. The extended search ended in the compromise choice of five alloys; 17-7 PH steel, 304 stainless steel, 347 stainless steel and 2024-T3 and 2024-TO aluminum.

General considerations. - An optimized linear energy source (expanding tube) system, as was considered in this program, is defined as that system which provides the maximum energy output (work) while retaining minimum weight and size, and while retaining the integrity of the tube wall during unconstrained expansion.

In general, it may be said that there are two major considerations that go into the design of an optimized expanding tube system: the energy that is delivered to the wall of the tube, and the capability of the wall to withstand the application of energy and subsequently perform the intended work. The physical counterparts of these considerations are the linear explosive charge and the confining tube.

In the explosive charge, consideration was given to its size (explosive quantity), geometry, and performance characteristics. In the tubing, consideration was given to its alloy, condition, size, and physical makeup. The ensuing discussions will consider these parameters, both individually and in combination, in consideration of the theoretical optimum combination of materials that were eventually tested.

Tube expansion mechanisms. - As the expanding tube system approaches the theoretical optimum, i.e., lightest system yielding the greatest net energy, knowledge of the mechanisms by which the energy is transmitted by virtue of an expanding metal tube becomes increasingly important. These expansion mechanisms

must be considered in two ways: the localized metallurgical mechanisms, and the mechanisms of the tube as a pressure vessel. Both of these mechanisms were studied individually and jointly to the extent that each was applicable to this program.

Metallurgical considerations: The metallurgical mechanisms encountered in high strain-rate metal deformation are not precisely understood. A great deal of study of these mechanisms has been undertaken in recent years; however, many of the theorized metallurgical response characteristics have failed to correspond to empirical demonstrations.

Similarly, a great deal of empirical demonstration has been performed, but many times with sporadic results and often without thorough or convincing substantiation by metallurgical studies. As a result it was possible only to generalize in these two areas, and to postulate the suspected optimum combinations for further study.

It is well recognized that the physical properties of materials are usually considerably different under conditions of high-rate loading than under static loading. Metallurgically, certain metals with FCC grain boundary matrices demonstrate increased ductility, tensile strength, and yield strength as the rate of strain application is increased. Conversely, metals with a body centered cubic (BCC) lattice demonstrate brittleness at high deformation rates. Alloys with hexagonal close-packed (HCP) lattice seem to fall midway between these two extremes, some showing increased and some showing decreased ductility at high loading rates.

It has therefore been generally conceded that metals with an FCC lattice are more probable candidates for high-rate deformation applications, where ductility, yield, and tensile strength are critical. Such is the expanding tube system.

Mechanical considerations: Within the context of detonation hydrodynamics, the optimum expanding tube system may properly be considered as a pressure vessel, inasmuch as the flattened tube will normally (when fired unconstrained) revert to a round cross section having a diameter greater than the original before flattening, thereby indicating that the yield strength of the metal has been exceeded.

Certain of the FCC alloys, notably the austenitic steels, demonstrate overt strain hardening characteristics. In consideration of a radially expanding tube system, this characteristic is advantageous in that the uniform wall of the tube will (during expansion) transmit the stress to the adjacent fiber as the localized stress acts on the immediate fiber, thereby increasing the localized yield strength. The result is a uniform radial expansion that is minimally affected by non-uniformity of tube-wall characteristics e.g., thickness variations, flaws, metallurgical inconsistencies.

In this regard, the dynamic response to the metallurgical effects resultant from the production of tubing by the welding and drawing technique are not known, whereas the quality and uniform response to dynamic loading in seamless tubing has been verified at ET and elsewhere. For that reason, seamless tubing was used wherever possible in this program.

Pressure impulse mechanisms. - As mentioned previously, one of the two primary considerations in the design of a linear energy system is the energy source (detonating cord in this instance). In consideration of the preceding discussion of expansion mechanisms, the consideration is more properly defined as the pressure impulse delivered to the wall of the tube during detonation of the cord that will ultimately result in a given deformation or strain rate in the tube.

The significance and importance of defining this pressure profile is well recognized in the field of high-rate forming, where a variety of explosive types are utilized in combination with a variety of buffer materials to produce a desired impulse at the work piece. These systems range in pressure intensity from direct contact of explosives to the work piece to essentially hydroforming of the piece through air or water coupling. The important factor in any case is knowing the approximate desired impulse at the work piece. Production of that desired impulse is then normally arrived at by a combination of theoretical considerations and empirical analysis.

Tube expansion has been used for some time as a means of determining the formability of various metals by explosive impulse. This work has normally been conducted using pure high explosives such as RDX, PETN, or TNT, although the transfer coupling medium has varied considerably, generally ranging between air and a dense fluid. It was therefore difficult to determine the desired impulse geometry for an optimum system from this data to any degree much greater than might be postulated by experienced intuition.

Youngdahl (ref. 25) has conducted an extensive computerized analysis on the susceptibility of nuclear reactors to tube rupture. Youngdahl's analysis is directed toward predetermination of the unique impulse geometry that would result in rupture of the reactor tubes. His analysis, however, while revealing the worst impulse configuration, also reveals the most desirable impulse for non-rupturing expansion of the reactor tubes.

For the purposes of his analysis, Youngdahl defines the impulse shape in terms of geometry and "effective-load," which he further defines as the peak impulse divided by twice the mean time of the pulse. His analysis shows that for tubular materials of a rigid plastic nature, the final plastic deformation is almost completely determined by the impulse and the effective load associated with the pulse. He also has shown in his analysis the effect of four different pulse shapes on final deformation of the tube. These include, in descending order of effectiveness: rectangular impulse, triangular impulse, linear decay impulse, exponential decay impulse.

Without overemphasizing the applicability of Youngdahl's work to this program, it was concluded that the most desirable pulse shape for the purpose of tube expansion without rupture would be one having a rectangular pulse geometry, and an attending effective load that slightly exceeded the yield strength of the tube material, regardless of what that material might happen to be.

Actual measurement of the impulse delivered to the wall of the tube was somewhat difficult and not within the scope of this program. Shock levels and tube extension precluded the use of standard electrical strain gages in this application. It appeared that it might be feasible to apply a birefringent photoelastic coating to the tube exterior, and to photographically observe stress initiation and propagation. Correlation of initial strain onset, early expansion strain rates, and terminal tube diameter expansion rates could give a reasonable approximation of impulse geometry and effective load of the pulse arriving at the tube wall. This correlation was not done, however, but is recommended for further study.

The pressure impulse received at the tube wall may be modified by several methods. First, the detonating compound may be formulated so that its detonating characteristics meet the desired impulse. This might be done by the use of various pure high explosives such as RDX, HNS, nitroguanidine, etc., or by the use of a high explosive modified by the addition of a low explosive or deflagrating material. Explosive Technology's "Flashcord" is typical of the latter type of detonating cord, and consists of HNS, potassium perchlorate, and titanium powder.

Another method of obtaining the proper impulse at the tube wall is to place an attenuating material around the detonating cord prior to insertion in the tube so that the impulse of the detonation is modified by normalization of the peak impulse. Typically, this may be accomplished through the use of a fiberglass jacket braided over the detonating cord, or by the use of a metal or rubber sleeve over the cord.

A third approach is through the combination of methods one and two, that is, the use of an attenuating media in conjunction with a Flashcord-type detonating cord.

Preferred Tubing Materials. - Several factors governed the choice of candidate tubing materials. These were generally as follows:

a. Apparent metallurgical suitability under high loading rates.

b. Availability and cost in various sizes.

c. Compatibility with production processes.

d. Corrosion resistance (untreated).

e. Availability of other data on the material (for data extrapolation).

As noted previously, the desired properties of the tubing material when under high dynamic loading conditions are high tensile strength, high yield strength, and high ductility or elongation.

Almost all work to date at ET and most of the known work of other confined energy system investigators has centered on the use of various alloys of 300 series stainless steel seamless tubing in the fully annealed condition. The work at ET has centered specifically on 304 stainless steel in view of its apparent satisfaction of the greatest number of the aforementioned criteria.

During this program, dynamic response data were reviewed on approximately 50 different alloys. It should be noted that many of these data were in association with explosive forming of difficult-to-fabricate parts (large rocket motor domes) and, for that reason, many were of the more exotic alloys. A considerable percentage, however, were the more common alloys.

In addition to these materials, a review of the static or quasistatic properties of approximately 50 additional alloys was performed on the assumption that, in FCC lattice alloys, dynamic properties would improve over the noted static properties. From this review, the following alloys were deemed superior by virtue of their fit to the aforementioned criteria:

a. 17-7 PH Steel

b. Haynes 25 Steel

c. Rene 41 Steel

d. A-286 Steel

e. 304 Stainless Steel

f. 304 N Stainless Steel

g. 347 Stainless Steel

h. 2024-T3 Aluminum

i. 2024-TO Aluminum

The aluminum alloys were added in an effort to explore the full spectrum of linear energy output. After an exhaustive survey of tubing producers in the U.S., it was determined that the final choice of candidate materials would necessarily be made on the basis of availability and cost.

A small quantity of 17-7 PH tubing (clearly the leading candidate material) was located for initial evaluation. The second candidate chosen was 304 stainless steel, due primarily to its general suitability as well as to the fact that ET has considerable prior data on expanding tube systems employing this particular alloy (e.g., F-14 aircraft and Manned Orbiting Laboratory). The third material chosen was 2024-T3 aluminum in view of its potential applicability to low energy systems and due to the availability of dynamic response data on this alloy.

It should be noted that type 304 N stainless steel had just been introduced on the market and was not yet available in seamless tubing. Its characteristics however, are clearly superior to 304. It is therefore recommended that this alloy be considered at a later date, if possible.

The choice of tube diameter was primarily predicated on work previously conducted by ET which had established a significant data base. For that reason 3/8-inch diameter tubing was standard throughout the study. The wall thickness for the tubing was again predicated on previous ET data. The range of wall thicknesses previously ascertained by ET to be the practical limits were 0.035- and 0.065-inch. Therefore, the candidate alloys were procured in 3/8-inch diameter seamless tubing with 0.035- and 0.065-inch wall thicknesses.

Historical data.- Explosive Technology has developed several expanding tube separation systems and has conducted a significant number of tests under a variety of conditions, although not necessarily in a mode that would result in obtaining quantative data such as obtained with an energy sensor. Nevertheless, the data from other ET expanding tube programs are included in the Appendices.

Tube Assembly Evaluation

The preliminary tests conducted at the outset of the program were designed to expeditiously define the maximum energy output without tube rupture. The energy sensor fixturing experienced severe wear during these tests. As a result, these early test results exhibited a wider variability than was desirable. New holders of hardened tool steel were procured for the remainder of the test program. This modification eliminated significant wear. The early tests that were conducted with the degrading tooling are noted in the test result tabulation ("preliminary tests"). The energy values of these tests are believed to be subject to a variable error and are not considered in the conclusions.

A variety of tubing, explosive core loading and support material was incorporated into the evaluation test series of this program. Table I lists the test conditions and post-fire results of each test. The tube material analysis is graphically compared in Figure 5. Considering the same fixed parameters, the best energy output from each of the materials is plotted. This display describes the general energy-core load relationship and notes the fixed parameters. The relationship between optimum wall thickness for each tube material and diameter is shown in Figure 6 for 2024 aluminum alloy and in Figure 7 for Type 304 stainless steel for two wall thicknesses, 0.035-inch and 0.065-inch.

The optimum explosive core material had been determined by ET in previous tests (reference Figure 8 and Tables C-I and C-II, Appendix C). This core is HNS/Ti/ $KClO_4$ (STA) explosive.

The direct comparison of support materials is shown in Figures 9 and 10.

The most promising combination of materials was evaluated at high (+300°F) and low (-300°F) temperatures. The results of these tests are listed in Table III. A plot showing the trends is shown in Figures 11 and 12.

A setup was arranged using a Fastax camera in the streak mode to record on 16 mm film the X-SMDC tubing as it expands during functioning. The prism in the camera was removed and a 0.005 slit mask (aperture) was installed. This gives a continuous record at one point on the tube. Figure 13 illustrates the test setup. Figure 14 presents the results.

The plot at the left of the Figure is a graphical description of the dynamic condition of the tube before, during and after function. Time is on the vertical axis and tube surface location is on the horizontal axis.

CONCLUSIONS

The program to develop and evaluate an Advanced Confined Linear Energy Source involved a literature search followed by test evaluation of tube materials and sizes, support materials and explosive type.

Although, theoretically, some of the tube materials evaluated for use in an expanding tube concept appeared to offer an outstanding selection of characteristics, the practical limitation of availability precluded their incorporation into the test program. The materials that were tested were the best that were available at the time.

Because of the extremely large number of parameters, a single or very few tests at each selected level and combination were conducted. With some inherent variation in test results, the comparative data gives trends and energy values without a high statistical confidence level. The data may be used as a guide with the final development taking place in the specific application.

The results of tube material testing indicate the severe limitation of aluminum compared with a stainless steel (9.1 in.-lb vs. 91.1 in.-lb). It also indicates the superiority of Type 304 (91.1 in.-lb) over 347 (67.1 in.-lb) and 17-7 (25.0 in.-lb).

In addition to the tube material itself, the wall thickness was of importance. There will be an optimum wall thickness for each material and diameter. The heavier wall (0.065-inch) in the aluminum produced 9.1 in.-lb, whereas the thinner-wall (0.035-inch) aluminum tube assembly only produced 5.15 in.-lb at the core load increment below the rupture level. The 0.035-inch wall Type 304 stainless tube allowed 91.1 in.-lb energy output before rupture, whereas the 0.065-inch wall ruptured just after reaching a maximum output of 25.0 in.-lb.

Another parameter that effects the capability of the system is the support material between the X-Cord and the tubing. Several materials were tested and evaluated. Other programs conducted at ET using fiberglass have shown that other materials are superior for this purpose. Although directly comparative test results are not available, the best energy output obtained with 3/8-inch stainless steel tubing and the STA explosive core with fiberglass support material was a comparatively low 62.7 in.-lb.

The best support material tested was lead (Pb) for maximum energy output. Lead and silicone rubber were used extensively during the program. With 0.035-inch wall Type 304 tubing, the maximum energy attained with silicone rubber was 91.1 in.-lb compared with 155.4 in.-lb with the lead support material. A similar, but more dramatic, relationship holds true with 0.065-inch wall Type 304

stainless tubing. A maximum of 25.0 in.-lb was attained using silicone rubber, whereas 165.0 in.-lb resulted from using lead as the support material.

Before the actual testing phase of the program was underway, other in-house work indicated that the HNS/Ti/$KClO_4$ (STA) explosive cord provided increased energy when compared with straight HNS (SA) cord. The peak energy is somewhat reduced and the energy is released during a longer period of time. The HNS cord generates 140 in.-lb at 15 gr/ft core load whereas the STA mixture generates 155 in.-lb at 15 gr/ft in a 3/8- x 0.049-inch wall Type 304 stainless steel tubing. Further, at 18 gr/ft the STA mixture generates 198 in.-lb without tube rupture; the SA mixture ruptures the tubing at 19 gr/ft. The majority of the program was conducted with STA cord because of this advantage.

The effects of temperature on the functioning characteristics were studied. Generally, the -300°F environment decreases the energy output in both aluminum and stainless, and the +300°F environment allows a greater energy output but also increases the tendency toward rupture.

In conclusion, the optimum system based on these test results comprises HNS/Ti/$KClO_4$ explosive in an aluminum sheath, a lead support, and a 3/8-inch diameter 0.065-inch wall Type 304 stainless steel tube.

TABLE I. - TUBE ASSEMBLY EVALUATION TEST RESULTS

Test Fig.	Tube Size, inch		Tube Material		X-Cord		Support				Test Temp, °F	Post-Test Dimension, inch	Energy Output, in.-lb	Tube Cond:	
	O.D.	Wall	Alum.	SST	Type	Core Load gr/ft	Fg	Si	Pb	Al				OK	Rup
1	3/8*	0.035		304	STA	3.5		X			Amb	0.300	9.3	X	
1	3/8*	0.035		304	STA	8.0		X			Amb	0.332	61.5	X	
1	3/8*	0.035		304	STA	8.0		X			Amb	0.323	37.4	X	
1	3/8*	0.035		304	STA	8.0		X			Amb	0.325	32.4	X	
1	3/8*	0.035		304	STA	8.0		X			Amb	0.323	49.8	X	
1	3/8*	0.035		304	STA	8.0		X ①			Amb	0.289	23.7	X	
1	3/8*	0.035		304	STA	8.0		X			Amb	0.291	25.8	X	
1	3/8*	0.035		304	STA	8.0		X ①			Amb	0.293	7.3	X	
1	3/8	0.035		304	STA	8.0		X			Amb	0.326	39.7	X	
1	3/8	0.035		304	STA	8.0		X			Amb	0.330	45.2	X	
1	3/8*	0.035		304	STA	12.0		X			Amb	0.340	82.5	X	
1	3/8*	0.035		304	STA	12.0		X			Amb	0.338	78.0	X	
1	3/8*	0.035		304	STA	12.0		X ①			Amb	0.304	23.7	X	
1	3/8	0.035		304	STA	12.0		X			Amb	0.335	71.0	X	
1	3/8	0.035		304	STA	12.0		X			Amb	0.342	71.6	X	
1	3/8*	0.035		304	STA	16.0		X			Amb	0.347	99.8	X	
1	3/8*	0.035		304	STA	16.0		X			Amb	0.347	94.2	X	
1	3/8	0.035		304	STA	16.0		X			Amb	0.353	90.6	X	
1	3/8	0.035		304	STA	16.0		X			Amb	0.342	91.7	X	
1	3/8*	0.035		304	STA	20.0		X			Amb	~	~		X
1	3/8*	0.035		304	STA	20.0		X			Amb	~	81.7		X
1	3/8	0.035		304	STA	20.0		X			Amb	~	106.0		X
1	3/8	0.035		304	STA	20.0		X			Amb	~	91.7		X
1	3/8	0.028	2024-0		STA	2.5			X		Amb	0.275	5.1	X	
1	3/8	0.028	2024-0		STA	3.5			X		Amb	0.276	13.7	X	
1	3/8	0.035	2024-0		STA	3.5			X		Amb	0.274	9.9	X	
1	3/8	0.035	2024-0		STA	5.5			X		Amb	0.278	34.3		X
1	3/8	0.065	2024-0		STA	5.5			X		Amb	0.278	19.8	X	
1	3/8	0.065	2024-0		STA	8.0			X		Amb	0.280	48.5		X
1	3/8*	0.035	2024-T3		STA	2.5		X			Amb	0.289	8.6	X	
1	3/8*	0.035	2024-T3		STA	2.5		X			Amb	0.292	5.5	X	
1	3/8*	0.035	2024-T3		STA	3.0		X			Amb	0.296	13.3	X	
1	3/8*	0.035	2024-T3		STA	3.0		X			Amb	0.295	11.4	X	
1	3/8*	0.035	2024-T3		STA	3.5		X			Amb	0.295	15.9		X
1	3/8*	0.035	2024-T3		STA	3.5		X			Amb	0.286	13.4	X	

① Extrusion having same cross sectional area as 0.290 O.D. x 0.093 I.D., but triangular in shape.

* Preliminary tests.

TABLE I. - TUBE ASSEMBLY EVALUATION TEST RESULTS - Continued

Test Fig.	Tube Size, inch		Tube Material		X-Cord		Support				Test Temp, °F	Post-Test Dimension, inch	Energy Output, in.-lb	Tube Cond.	
	O.D.	Wall	Alum.	SST	Type	Core Load gr/ft	Fg	Si	Pb	Al				OK	Rup
1	3/8	0.065	2024-T3		STA	8.0		X			Amb	0.303	16.8		X
1	3/8	0.035	2024-0		STA	2.5		X			Amb	0.294	4.6	X	
1	3/8	0.035	2024-0		STA	2.5		X			Amb	0.295	4.5	X	
1	3/8	0.035	2024-0		STA	3.0		X			Amb	0.297	5.8	X	
1	3/8	0.035	2024-0		STA	3.0		X			Amb	0.295	4.5	X	
1	3/8	0.035	2024-0		STA	3.5		X			Amb	0.298	8.3		X
1	3/8	0.035	2024-0		STA	3.5		X			Amb	0.296	6.5		X
1	3/8	0.065	2024-0		STA	3.5		X			Amb	0.276	3.3	X	
1	3/8	0.065	2024-0		STA	3.5		X			Amb	0.277	3.5	X	
1	3/8	0.065	2024-0		STA	5.5		X			Amb	0.293	4.6	X	
1	3/8	0.065	2024-0		STA	5.5		X			Amb	0.301	3.4	X	
1	3/8	0.065	2024-0		STA	8.0		X			Amb	0.289	7.5	X	
1	3/8	0.065	2024-0		STA	8.0		X			Amb	0.303	10.7	X	
1	3/8	0.028		304	STA	10.0			X		Amb	0.298	109.7	X	
1	3/8	0.028		304	STA	12.0			X		Amb	0.305	120.0	X	
1	3/8	0.028		304	STA	14.0			X		Amb	0.305	153.4		X
1	3/8	0.028		304	STA	16.0			X		Amb	0.300	186.9		X
1	3/8	0.035		304	STA	16.0			X		Amb	0.288	155.4	X	
1	3/8	0.035		304	STA	18.0			X		Amb	0.287	160.6		X
1	3/8	0.035		304	STA	20.0			X		Amb	0.286	158.6		X
1	3/8	0.035		304	STA	22.0			X		Amb	0.286	177.6		X
1	3/8	0.065		304	STA	16.0			X		Amb	0.283	125.1	X	
1	3/8	0.065		304	STA	18.0			X		Amb	0.286	165.0	X	
1	3/8	0.065		304	STA	20.0			X		Amb	0.283	167.6		X
1	3/8	0.065		304	STA	22.0			X		Amb	0.282	173.9		X
1	3/8*	0.065		304	STA	8.0		X			Amb	0.284	3.2	X	
1	3/8*	0.065		304	STA	8.0		X			Amb	0.284	6.4	X	
1	3/8	0.065		304	STA	8.0		X			Amb	0.274	10.4	X	
1	3/8	0.065		304	STA	8.0		X			Amb	0.280	11.4	X	
1	3/8*	0.065		304	STA	12.0		X			Amb	0.286	19.1	X	
1	3/8*	0.065		304	STA	12.0		X			Amb	0.287	24.9	X	
1	3/8	0.065		304	STA	12.0		X			Amb	0.279	21.3	X	
1	3/8	0.065		304	STA	12.0		X			Amb	0.280	23.3	X	
1	3/8*	0.065		304	STA	16.0		X			Amb	0.290	43.6	X	
1	3/8*	0.065		304	STA	16.0		X			Amb	0.292	38.7	X	
1	3/8	0.065		304	STA	16.0		X			Amb	0.291	27.3	X	

TABLE I. - TUBE ASSEMBLY EVALUATION TEST RESULTS - Concluded

Test Fig.	Tube Size, inch		Tube Material		X-Cord		Support				Test Temp, °F	Post-Test Dimension, inch	Energy Output, in.-lb	Tube Cond.	
	O.D.	Wall	Alum.	SST	Type	Core Load gr/ft	Fg	Si	Pb	Al				OK	Rup
1	3/8	0.065		304	STA	16.0		X			Amb	0.285	22.8	X	
1	3/8	0.065		304	STA	20.0		X			Amb	~	84.4		X
1	3/8*	0.065		304	STA	20.0		X			Amb	~	97.8		X
1	3/8*	0.065		304	STA	20.0		X			Amb	~	93.8		X
1	3/8	0.065		304	STA	20.0		X			Amb	~	106.7		X
1	3/8*	0.065		304	STA	24.0		X			Amb	~	167.5		X
1	3/8	0.065		304	STA	24.0		X			Amb	~	199.0		X
1	3/8	0.065		304	STA	24.0		X			Amb	~	141.0		X
1	3/8*	0.062		17-7	STA	16.0		X			Amb	0.289	49.7	X	
1	3/8	0.062		17-7	STA	16.0		X			Amb	0.298	22.8	X	
1	3/8	0.062		17-7	STA	16.0		X			Amb	0.287	27.3	X	
1	3/8*	0.062		17-7	STA	20.0		X			Amb	~	145.5		X
1	3/8	0.062		17-7	STA	20.0		X			Amb	0.297	94.3		X
1	3/8	0.062		17-7	STA	20.0		X			Amb	0.296	93.7		X
1	3/8	0.062		17-7	STA	24.0		X			Amb	0.296	131.5		X
1	3/8	0.062		17-7	STA	24.0		X			Amb	0.298	163.2		X
1	3/8	0.035		347	STA	8.0		X			Amb	0.335	22.5	X	
1	3/8	0.035		347	STA	8.0		X			Amb	0.333	20.7	X	
1	3/8	0.035		347	STA	12.0		X			Amb	0.334	68.4	X	
1	3/8	0.035		347	STA	12.0		X			Amb	0.335	66.3	X	
1	3/8	0.035		347	STA	16.0		X			Amb	0.338	59.2		X
1	3/8	0.035		347	STA	16.0		X			Amb	0.353	60.3	X	
1	3/8	0.035		347	STA	20.0		X			Amb	0.297	84.0		X
1	3/8	0.035		347	STA	20.0		X			Amb	0.296	87.0		X
1	3/8	0.065		347	STA	16.0		X			Amb	0.291	32.5	X	
1	3/8	0.065		347	STA	16.0		X			Amb	0.291	30.2		X
1	3/8	0.065		347	STA	20.0		X			Amb	0.288	88.1		X
1	3/8	0.065		347	STA	20.0		X			Amb	0.328	161.0		X

TABLE II. - TUBE MATERIALS SURVEYED

No.	Material	Mechanical Properties at 70°F Tensile Strength (1,000 psi)	Yield Strength (1,000 psi)	Elongation (% in 2 in.)
1	304 Stainless	85	35	55
2	17-7 PH	130	40	61
3	17-10 PH	89	37	70
4	AM-350	160	55	40
5	HMN	116	56	57
6	Tenelon	125	70	45
7	L-605	131	61	49
8	Inconel 600	80	30	50
9	Nickel 200	80	30	35
10	Cartridge Brass	47	15	65
11	Cartridge Brass	52	20	55
12	Monel	70	25	50
13	Hastelloy B	121	57	63
14	Hastelloy B	172	83	58
15	Hastelloy B	135	60	50
16	Nickel D	86	34	40
17	201 Stainless	115	55	55
18	202 Stainless	105	55	55
19	301 Stainless	110	40	60
20	Nickel 200	55	15	50
21	309 Stainless	100	50	50
22	Rene 41	--	--	--
23	A-286	146	100	25
24	17.5% Cr, 4.3% Ni, 5.4% Mn	138	41	65
25	Haynes 25	155	70	55
26	304-N Stainless	105	69	50
27	211 Stainless	89	36	59
28	216 Stainless	100	55	45
29	304 Stainless	115	95	25
30	18-18-2 Stainless	81	35	54
31	E-Brite 26-1 Stainless	71	52	30
32	304-N Stainless (Cond. CW)	150	123	22
33	Custom 450 Stainless	196	185	14
34	21-6-9 Stainless	150	125	23
35	AM-350 Stainless	195	170	22
36	Inconel 600 Nickel-Base Alloy	100	50	40
37	Inconel 601 Nickel-Base Alloy	--	--	--
38	Almar 362 Stainless	180	160	18
39	PH-15-7 Mo Stainless	240	225	6

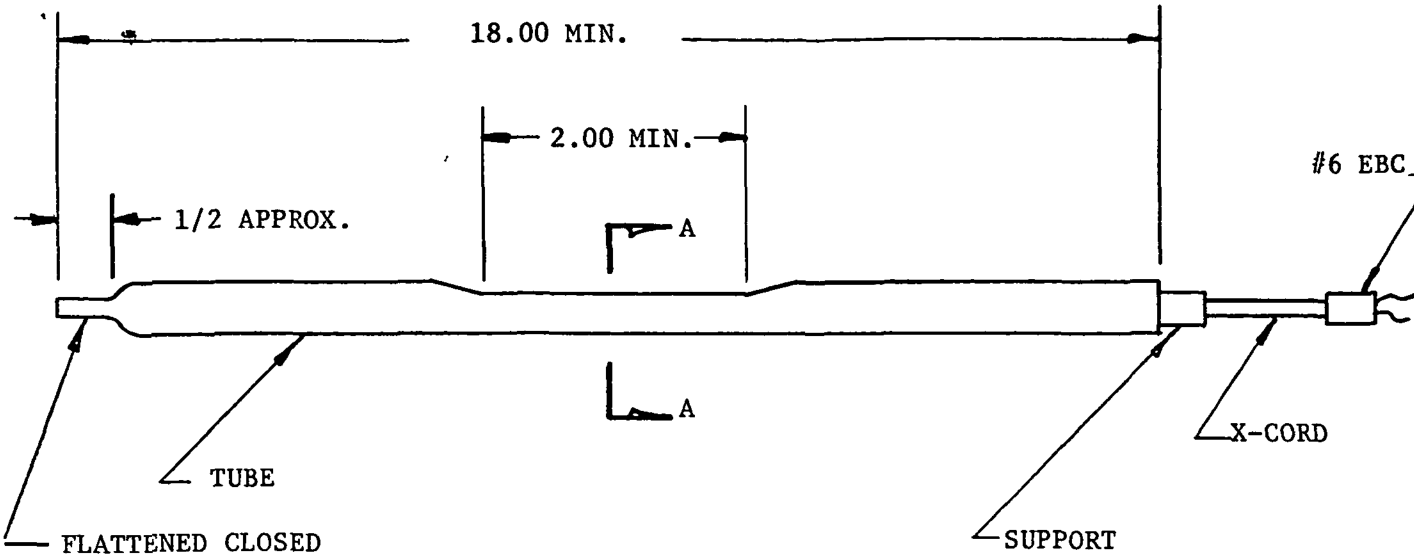
TABLE II. - TUBE MATERIALS SURVEYED - Continued

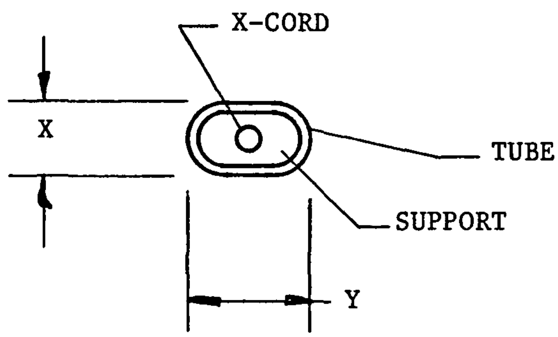
No.	Material	Mechanical Properties at 70°F: Tensile Strength (1,000 psi)	Yield Strength (1,000 psi)	Elongation (% in 2 in.)
40	Inconel X-750 Nickel-Base Alloy	180	136	24
41	IN-744 Stainless	112	92	20
42	Hastelloy X Nickel-Base Alloy	130	70	40
43	Inconel 625 Nickel-Base Alloy	130	70	45
44	Commercially Pure Titanium	90	75	12
45	Hastelloy C Nickel-Base Alloy	128	68	49
46	Hastelloy B Nickel-BAse Alloy	121	56	63
47	Waspalloy Nickel-Base Alloy	185	115	25
48	Inconel 718 Nickel-Base Alloy	200	165	22
49	Haynes 25 Cobalt-Base Alloy	144	66	58
50	3/2.5 Titanium	135	110	12
51	TD Nickel	65	45	15
52	Columbium	45	35	30
53	Tantalum	50	45	40
54	6/4 Titanium	135	125	12
55	Beta Titanium	220	207	8

TABLE III. - THERMAL CAPABILITIES TEST RESULTS

Test Fig.	Tube Size, inch		Tube Material		X-Cord		Support				Test Temp, °F	Post-Test Dimension, inch	Energy Output, in.-lb	Tube Cond.	
	O.D.	Wall	Alum.	SST	Type	Core Load gr/ft	Fg	Si	Pb	Al				OK	Rup
1 & 3	3/8	0.035	2024-0		STA	2.5		X			-300	0.280	8.9	X	
1 & 4	3/8	0.035	2024-0		STA	2.5		X			+300	0.291	11.2	X	
1 & 3	3/8	0.035	2024-0		STA	3.5		X			-300	0.301	9.9		X
1 & 4	3/8	0.035	2024-0		STA	3.5		X			+300	0.302	16.9		X
1 & 3	3/8	0.065	2024-0		STA	3.5		X			-300	0.276	1.1	X	
1 & 4	3/8	0.065	2024-0		STA	3.5		X			+300	0.273	3.6	X	
1 & 3	3/8	0.065	2024-0		STA	5.5		X			-300	0.290	2.8	X	
1 & 4	3/8	0.065	2024-0		STA	5.5		X			+300	0.280	4.9	X	
1 & 3	3/8	0.065	2024-0		STA	8.0		X			-300	0.286	22.8		X
1 & 4	3/8	0.065	2024-0		STA	8.0		X			+300	0.292	19.9		X
1 & 4	3/8	0.035		304	STA	12.0			X		+300	0.300	111.1	X	
1 & 3	3/8	0.035		304	STA	12.0			X		-300	0.286	52.5	X	
1 & 4	3/8	0.035		304	STA	14.0			X		+300	0.296	207.7		X
1 & 3	3/8	0.035		304	STA	14.0			X		-300	0.300	81.2	X	
1 & 4	3/8	0.035		304	STA	16.0			X		+300	0.303	225.3		X
1 & 3	3/8	0.035		304	STA	16.0			X		-300	0.303	95.02	X	
1	3/8	0.035		304	STA	16.0				X①	Amb	0.279	32.02	X	
1 & 3	3/8	0.035		304	STA	5.5		X	X		-300	0.285	17.1	X	
1 & 4	3/8	0.035		304	STA	5.5		X			+300	0.313	22.0	X	
1 & 3	3/8	0.035		304	STA	8.0		X			-300	0.314	25.6	X	
1 & 4	3/8	0.035		304	STA	8.0		X			+300	0.330	28.5	X	
1 & 3	3/8	0.035		304	STA	12.0		X			-300	0.322	50.6	X	
1 & 4	3/8	0.035		304	STA	12.0		X			+300	0.340	43.9	X	
1 & 3	3/8	0.065		304	STA	5.5		X			-300	0.275	6.4	X	
1 & 4	3/8	0.065		304	STA	5.5		X			+300	0.276	5.1	X	
1 & 3	3/8	0.065		304	STA	8.0		X			-300	0.274	7.4	X	
1 & 4	3/8	0.065		304	STA	8.0		X			+300	0.278	10.3	X	
1 & 3	3/8	0.065		304	STA	12.0		X			-300	0.275	17.1	X	
1 & 4	3/8	0.065		304	STA	12.0		X			+300	0.281	29.7	X	

① Support was 6061-T651 aluminum.

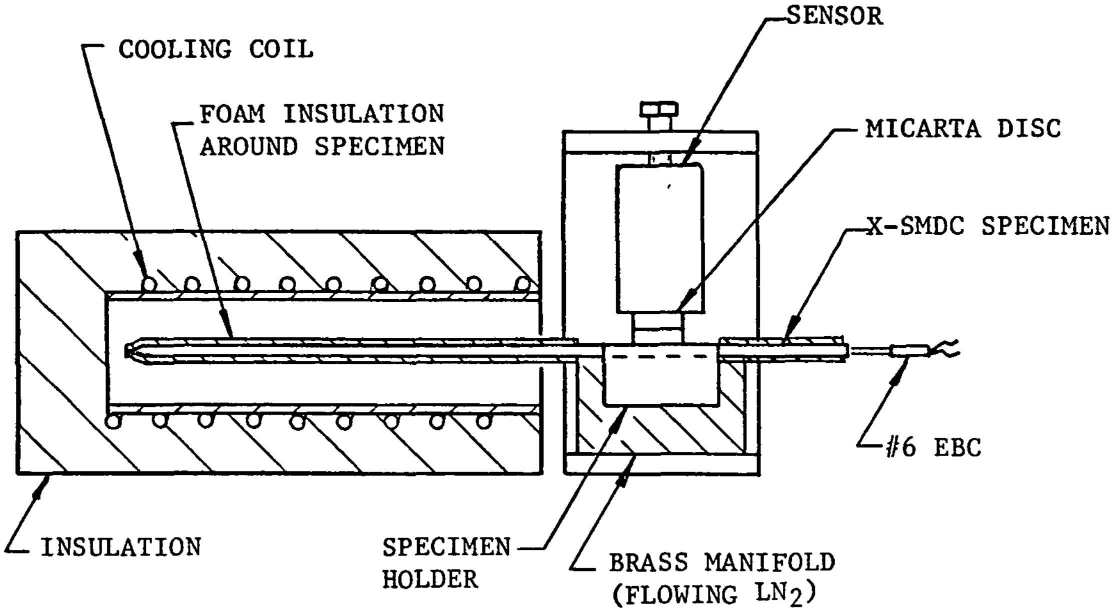




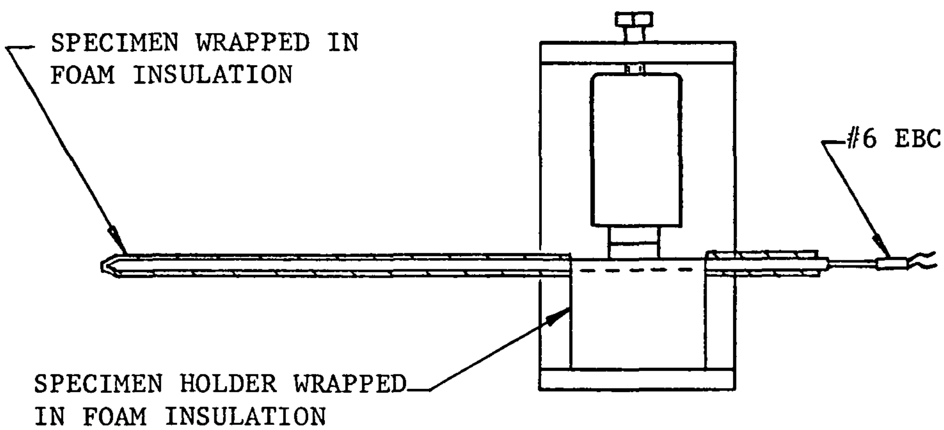
Section A-A. Typical Section Through Flattened Area

TABULATION		
TUBE OD	"X" DIM.	"Y" DIM.
1/4	0.176/0.181	0.285/0.295
5/16	0.224/0.229	0.365/0.375
3/8	0.267/0.272	0.440/0.450
1/2	0.360/0.365	0.585/0.595

Figure 1. Open End Test Configuration for Tube Assembly Evaluation



LOW TEMPERATURE TEST SETUP
(SEE FIGURE 3)



HIGH TEMPERATURE TEST SETUP
(SEE FIGURE 4)

NOTES: (1) Sensor assembled in setup after temperature stabilization.
(2) LN_2 flow through low temperature setup for 30 minutes for specimen to reach -300°F.

Figure 2. Temperature Conditioning Setups

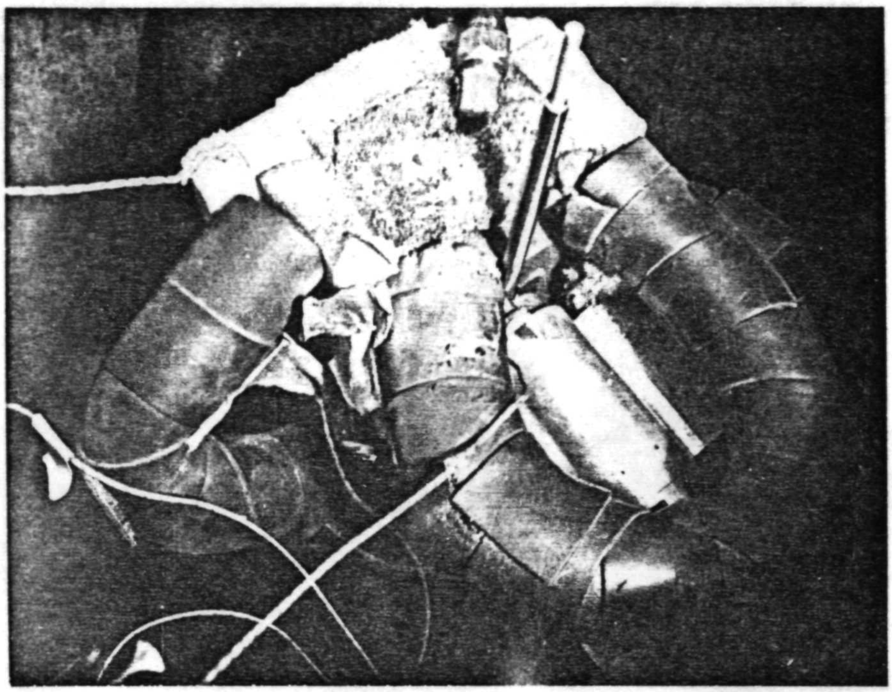


Figure 3. Low Temperature Test Setup

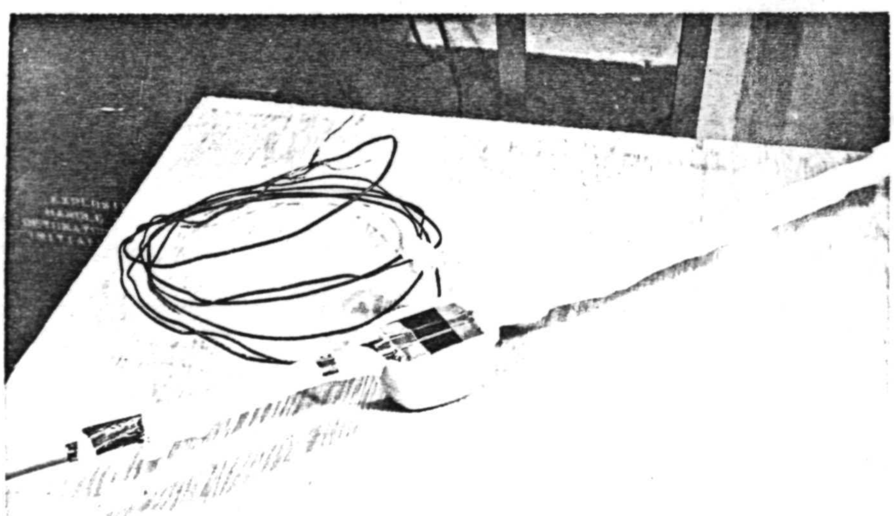
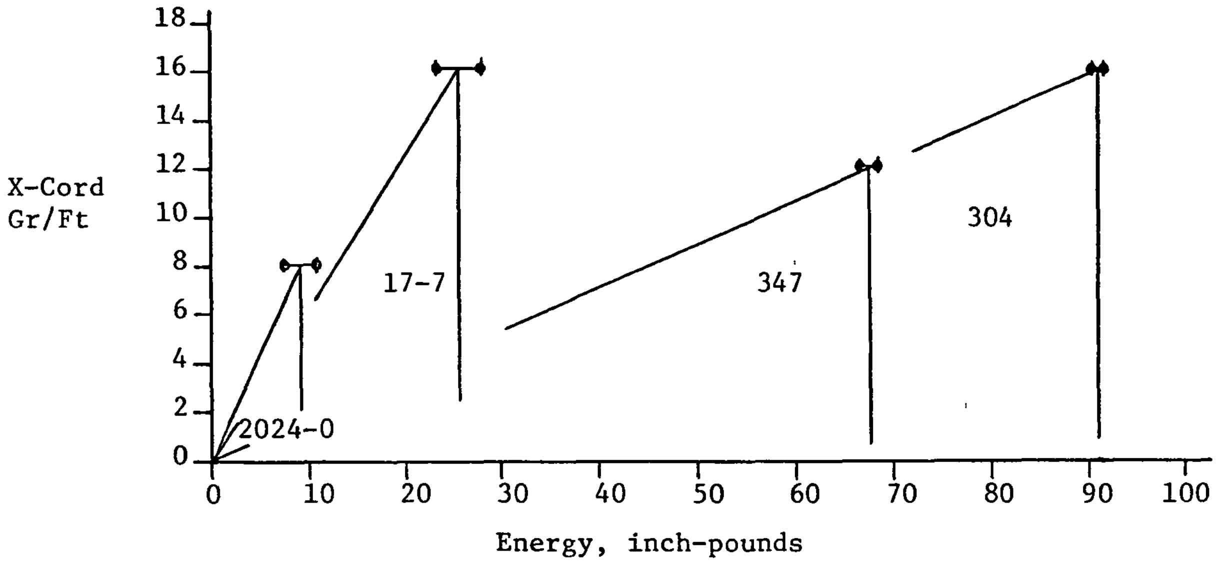


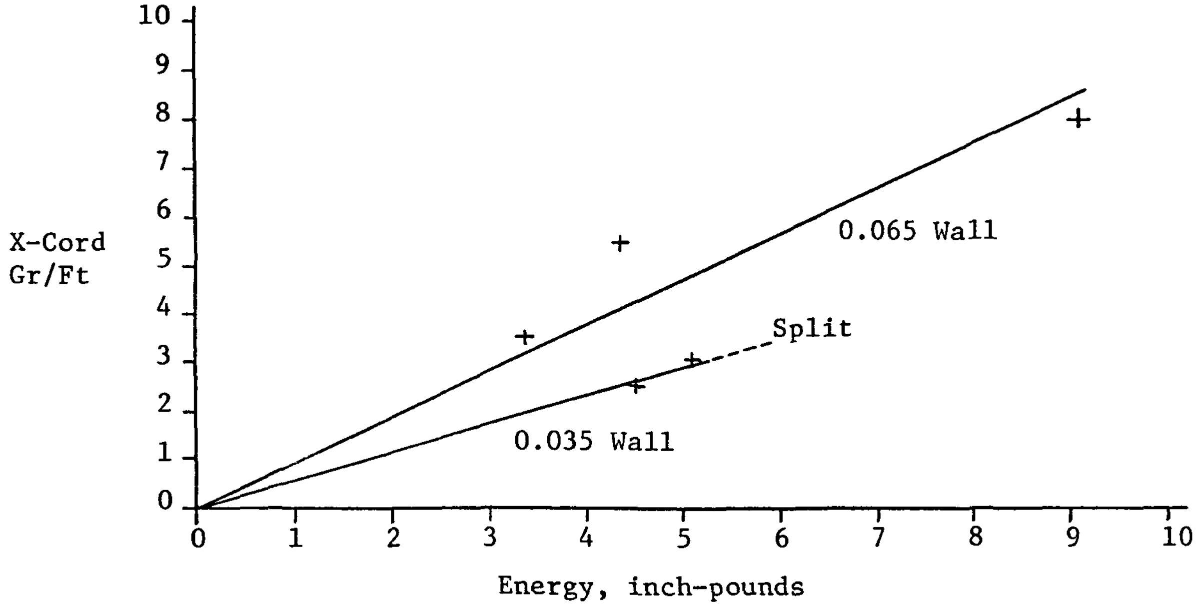
Figure 4. High Temperature Test Setup



Fixed Parameters

STA Silicone Rubber Support
Room Temp. 2 Data Point Average
3/8 O.D.

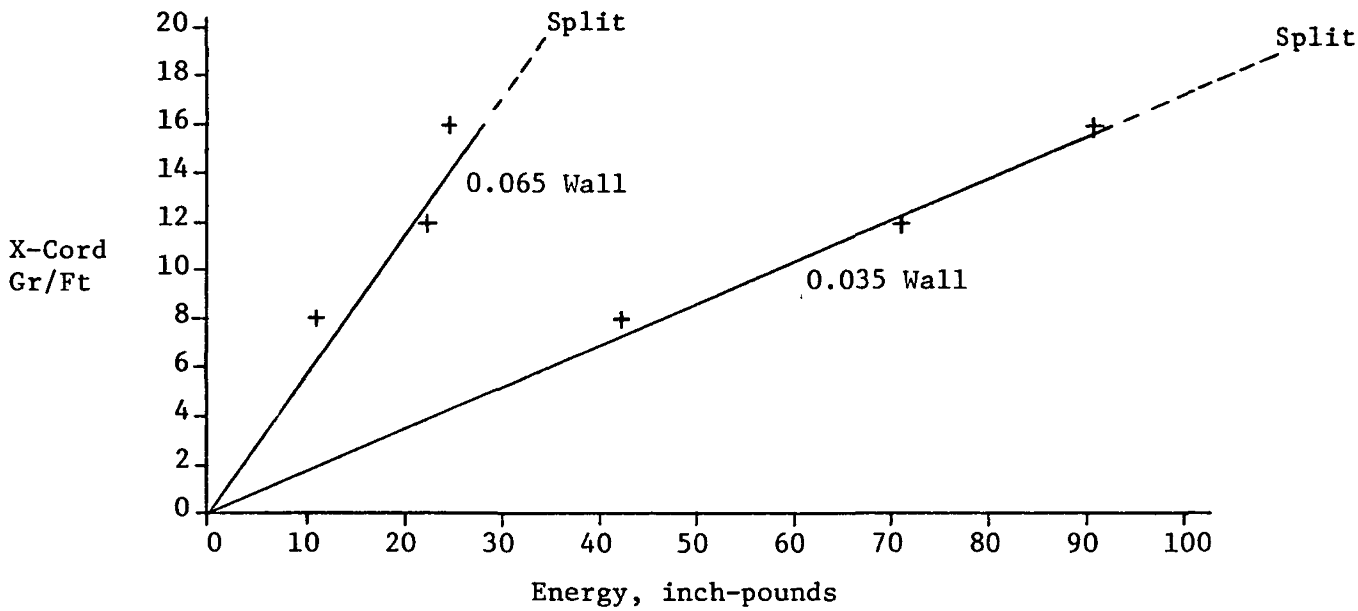
FIGURE 5. - OPTIMUM OUTPUT ENERGY FOR VARIOUS TUBE MATERIALS



Fixed Parameters

STA	2024 Tubing
3/8 O.D.	Silicone Rubber Support
Room Temp.	2 Data Point Average

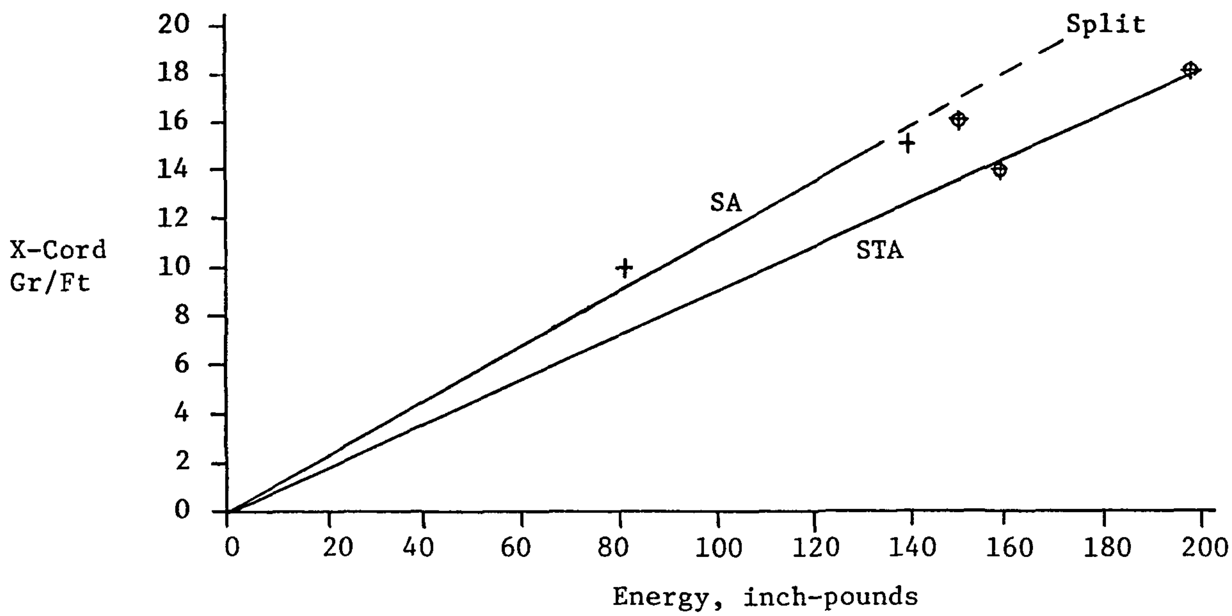
FIGURE 6. - OUTPUT ENERGY FOR VARIOUS WALL THICKNESSES, 2024 AL ALLOY



<u>Fixed Parameters</u>

STA	304 Tubing
3/8 O.D.	Silicone Rubber Support
Room Temp.	2 Data Point Average

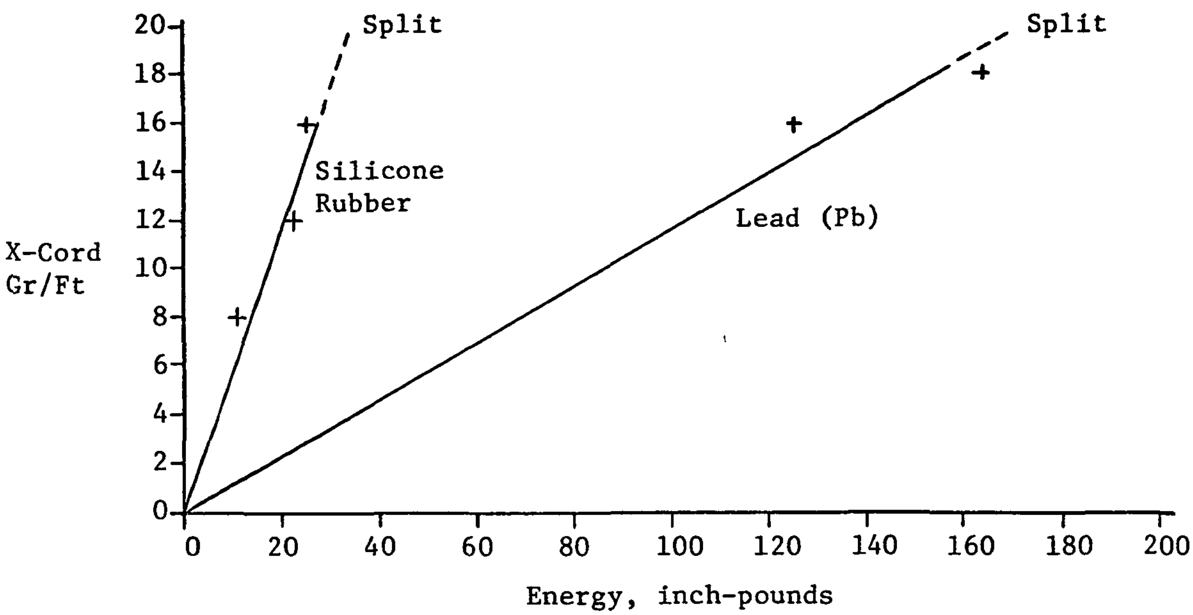
FIGURE 7. - OUTPUT ENERGY FOR VARIOUS WALL THICKNESSES, 304 SST



Fixed Parameters

3/8 O.D.	304 Tubing
Room Temp.	0.049 Wall
	Lead (Pb) Support
	2 Data Point Average

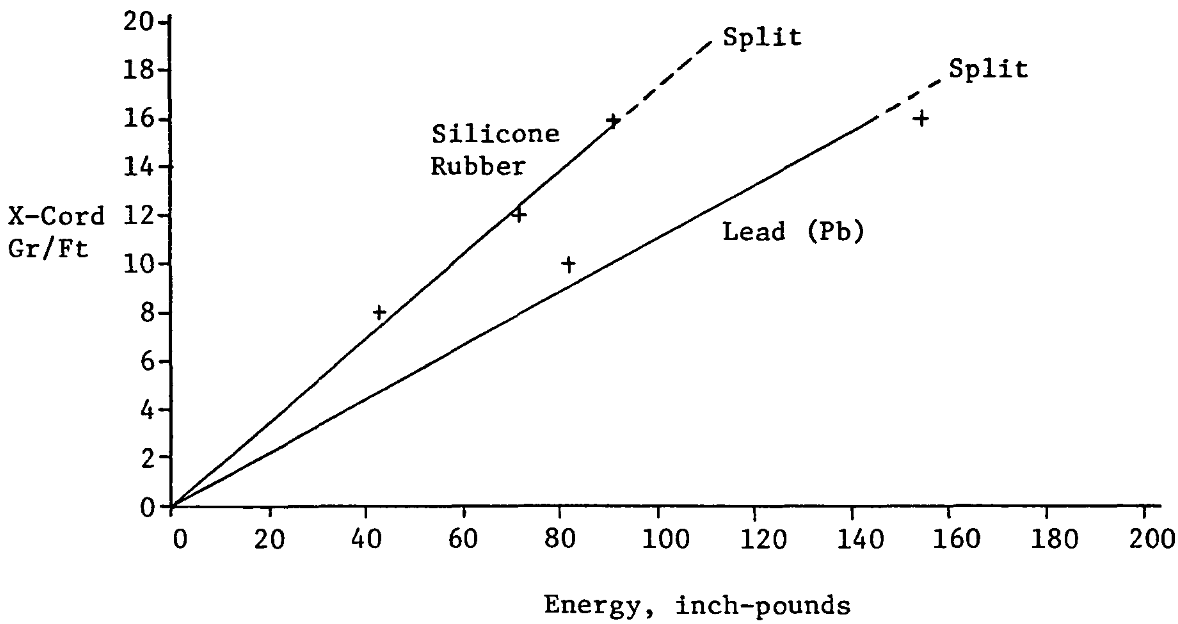
FIGURE 8. - COMPARISON OF EXPLOSIVE CORE MATERIAL, ENERGY OUTPUT



Fixed Parameters

STA	304 Tubing
3/8 O.D.	0.065 Wall
Room Temp.	2 Data Point Average

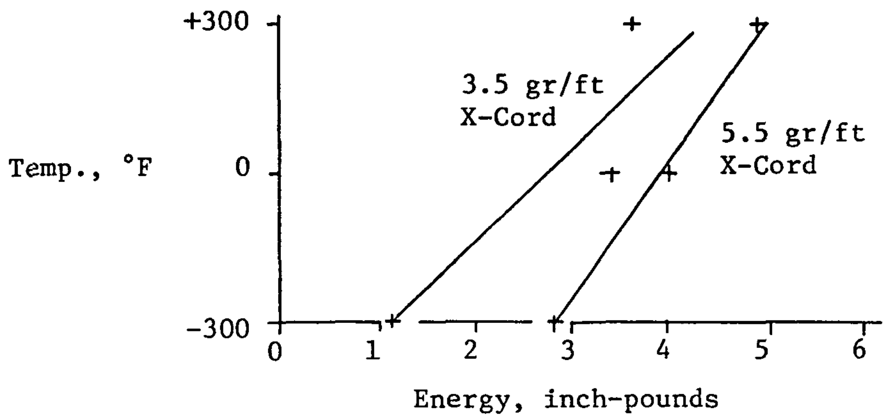
FIGURE 9. - OUTPUT ENERGY FOR VARIOUS SUPPORT MATERIALS



Fixed Parameters

STA	304 Tubing
3/8 O.D.	0.035 Wall
Room Temp.	2 Data Point Average for Silicone
	Single Test Data Point for Lead

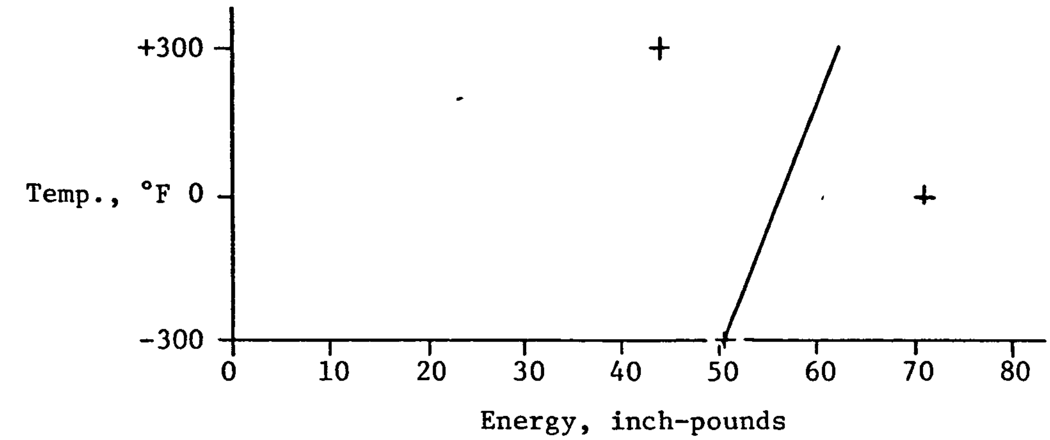
FIGURE 10. - OUTPUT ENERGY FOR VARIOUS SUPPORT MATERIALS



Fixed Parameters

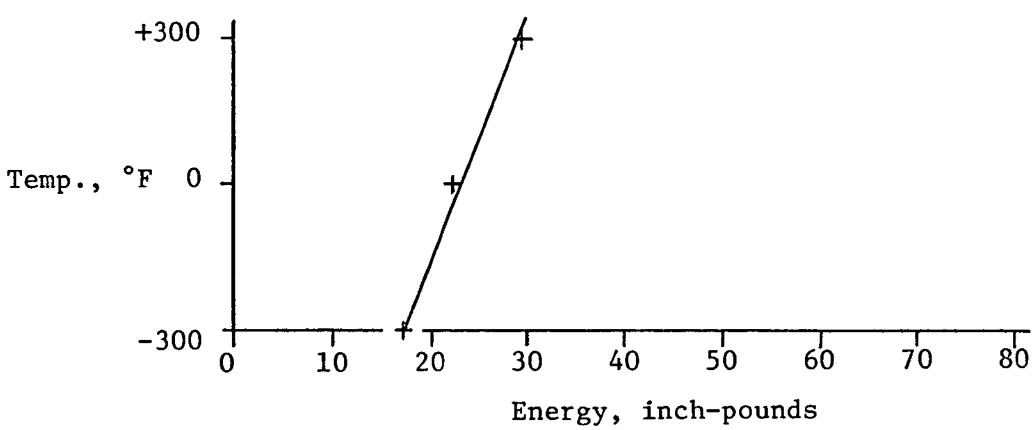
STA	
3/8 O.D.	Silicone Rubber Support
0.065 Wall	Single Test Data Point
2024-0 Tubing	

FIGURE 11. - OUTPUT ENERGY AT VARIOUS TEMPERATURES



Fixed Parameters

STA	Silicone Rubber Support
3/8 O.D.	12 gr/ft X-Cord
0.035 Wall	Single Test Data Point
304 Tubing	



Fixed Parameters

STA	Silicone Rubber Support
3/8 O.D.	12 gr/ft X-Cord
0.065 Wall	Single Test Data Point
304 Tubing	

FIGURE 12. - OUTPUT ENERGY AT VARIOUS TEMPERATURES

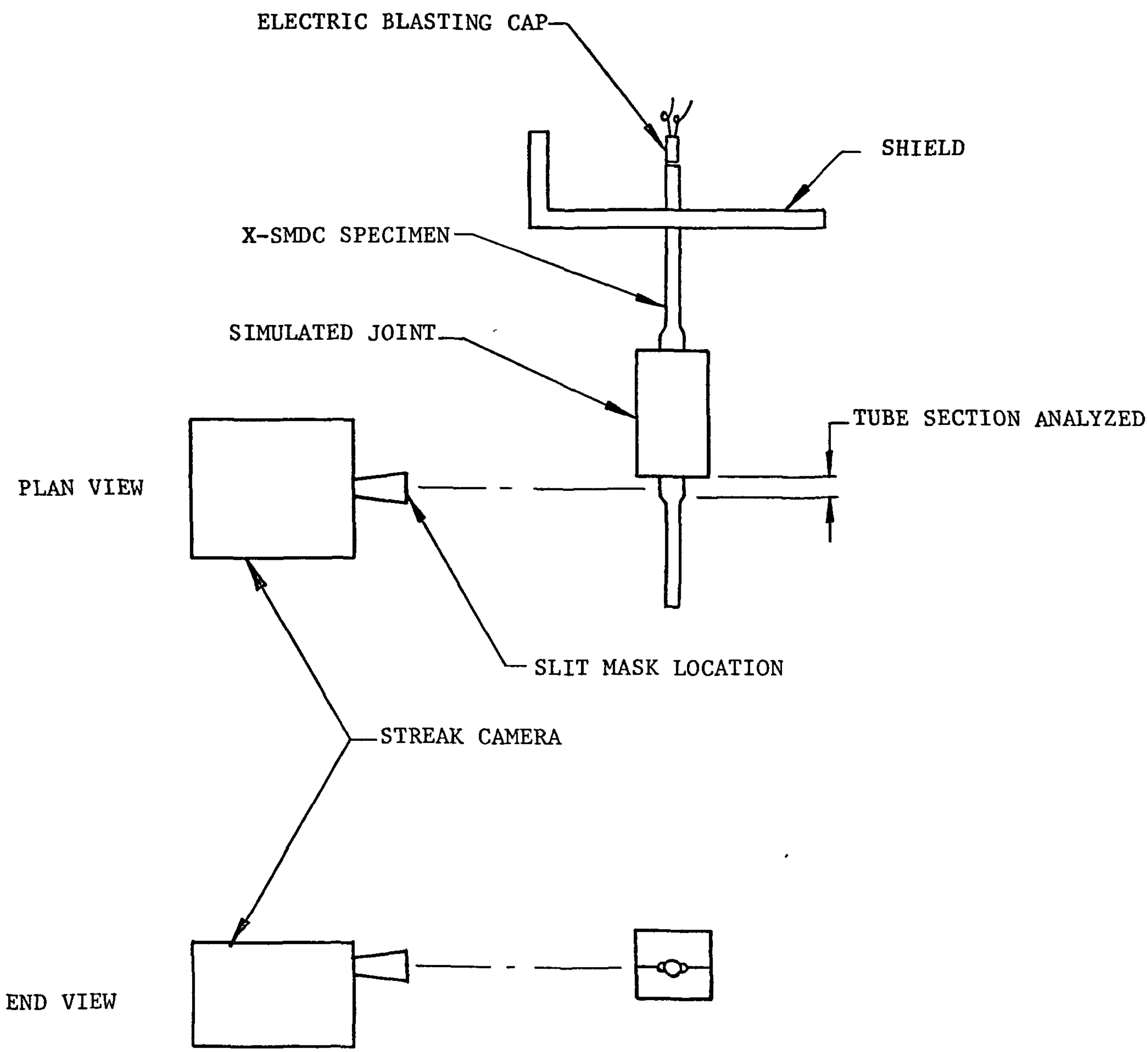
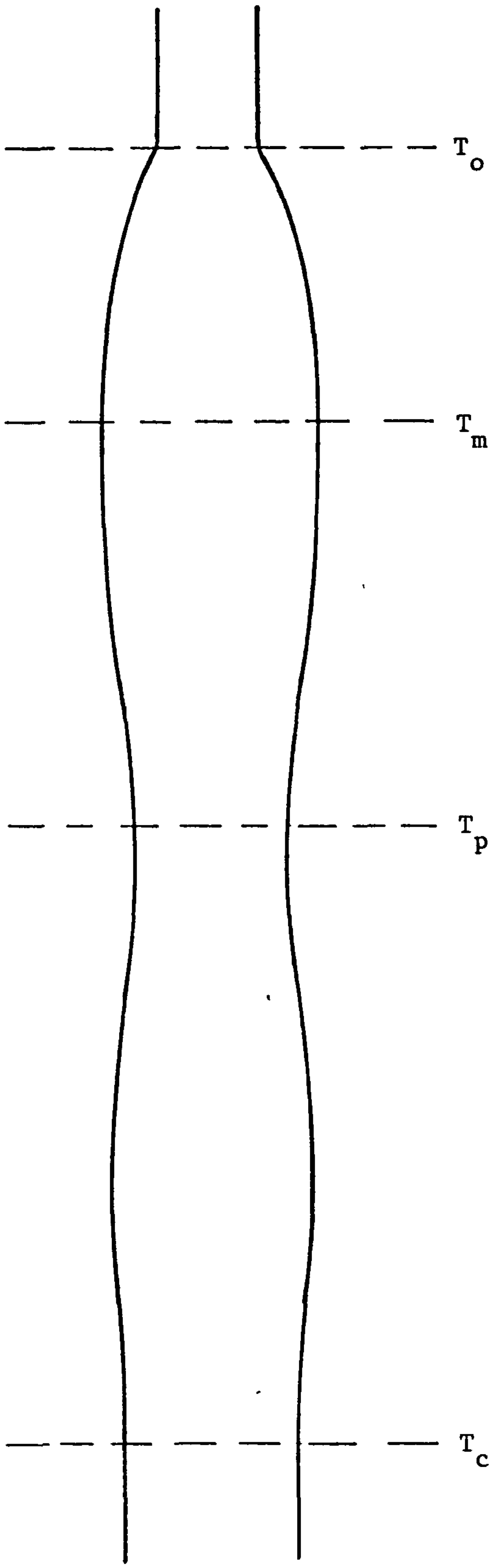


Figure 13. - Streak Camera Setup for Dynamic Tube Expansion Record



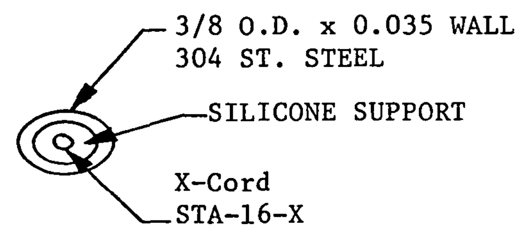
T_o = Start of Event

T_m = Point of Maximum Expansion

T_p = Approximate Midpoint of Event

T_c = Completion of Event

Tabulation		
Location	Elapsed Time	Dimension
T_o	Start	0.270
T_m	35.3 μsec	0.577
T_p	82.2 μsec	0.405
T_c	160.1 μsec	0.458



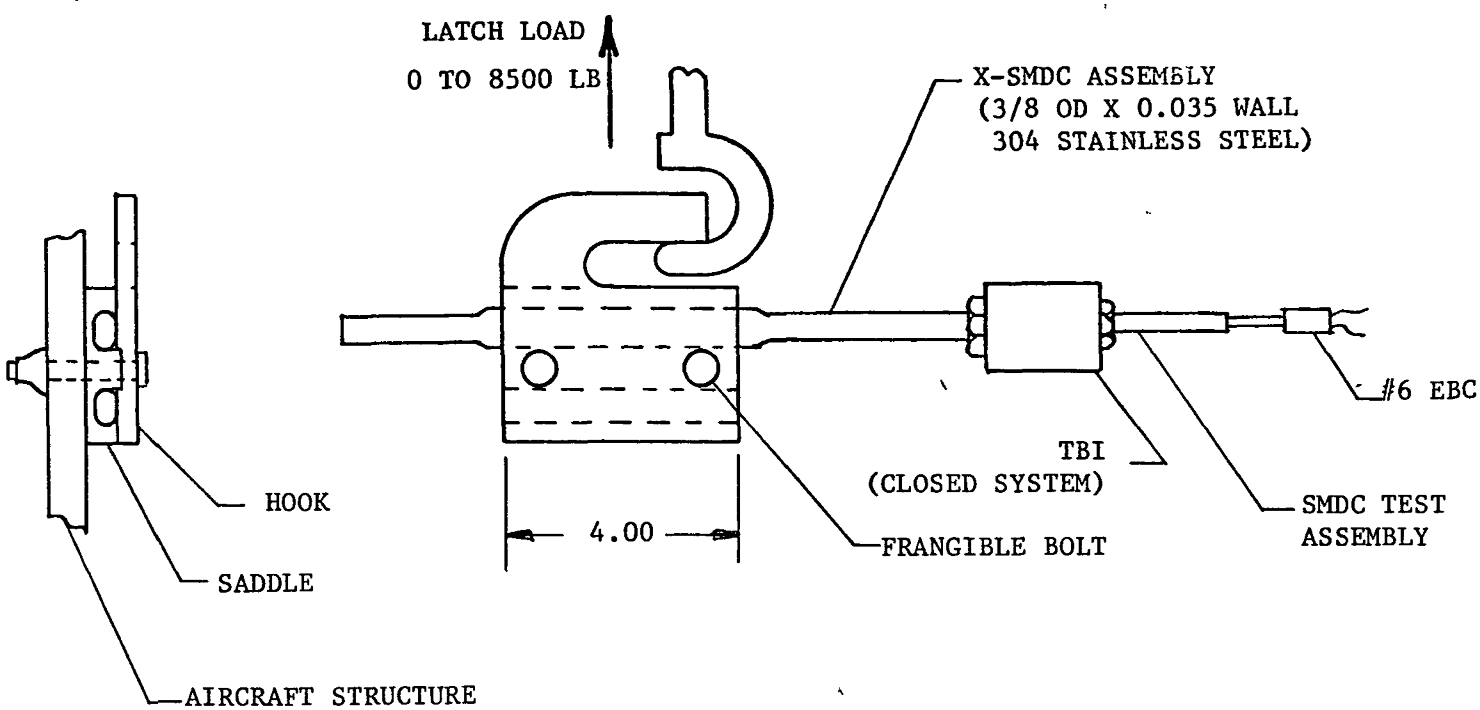
Cross Section of Specimen Tested

Figure 14. - Data Reduction of X-SMDC Tubing During Expansion

APPENDIX A - F-14 TEST DATA

The F-14 aircraft incorporates an expanding tube system used in the removal of the canopy in an abort situation. This system was developed at ET and is presently in the qualification program.

Basically, the system incorporates a saddle and hook arrangement at seven locations on each side of the aircraft structure. A mating hook is attached to the canopy. Upon initiation of the system the X-SMDC expands, failing a special fastener in tension. The hook disengages, allowing the removal of the canopy. Expansion data from this system is delineated in Figure A-1.



NO. OF TESTS[a]	X-SMDC CONFIG. X-CORD TYPE	X-SMDC CONFIG. X-CORD CORE LOAD	FRANGIBLE BOLT STRENGTH (LB TENSILE)	TEST TEMP. (°F)
2	SA	8[b]	3200	-65
2	SA	8[b]	3200	+200
125[d]	SA	10	3750	-65
150[d]	SA	10	3750	Amb.
125[d]	SA	10	3750	+200
4	SA	10	3750	+350
4	SA	13[c]	3750	+200

NOTES: [a]No tubing ruptures were encountered. ALL BOLTS WERE BROKEN.

[b]To demonstrate performance at 75-percent nominal core load.

[c]To demonstrate structural integrity at 125-percent nominal core load.

[d]For 300 observations, minimum expansion over temperature range of -65° to +200°F under varying latch loads from 0 to 8500 lb is 0.291-inch at 2σ limit.

Figure A-1. Test Configuration of Expanding Tube Used for F-14 Canopy Removal

APPENDIX B - SEPARATION TEST DATA

ET has evaluated the X-SMDC for application as a structural severance device. One application considered was removal of a nose cone or booster. In this application shear pins were used and a mass-simulating separation weight was incorporated in the test. See Figure B-1 for setup and test results. The other application considered was separation of an integral structure where fasteners may not be able to be used. See Figure B-2 for setup and test results of this application.

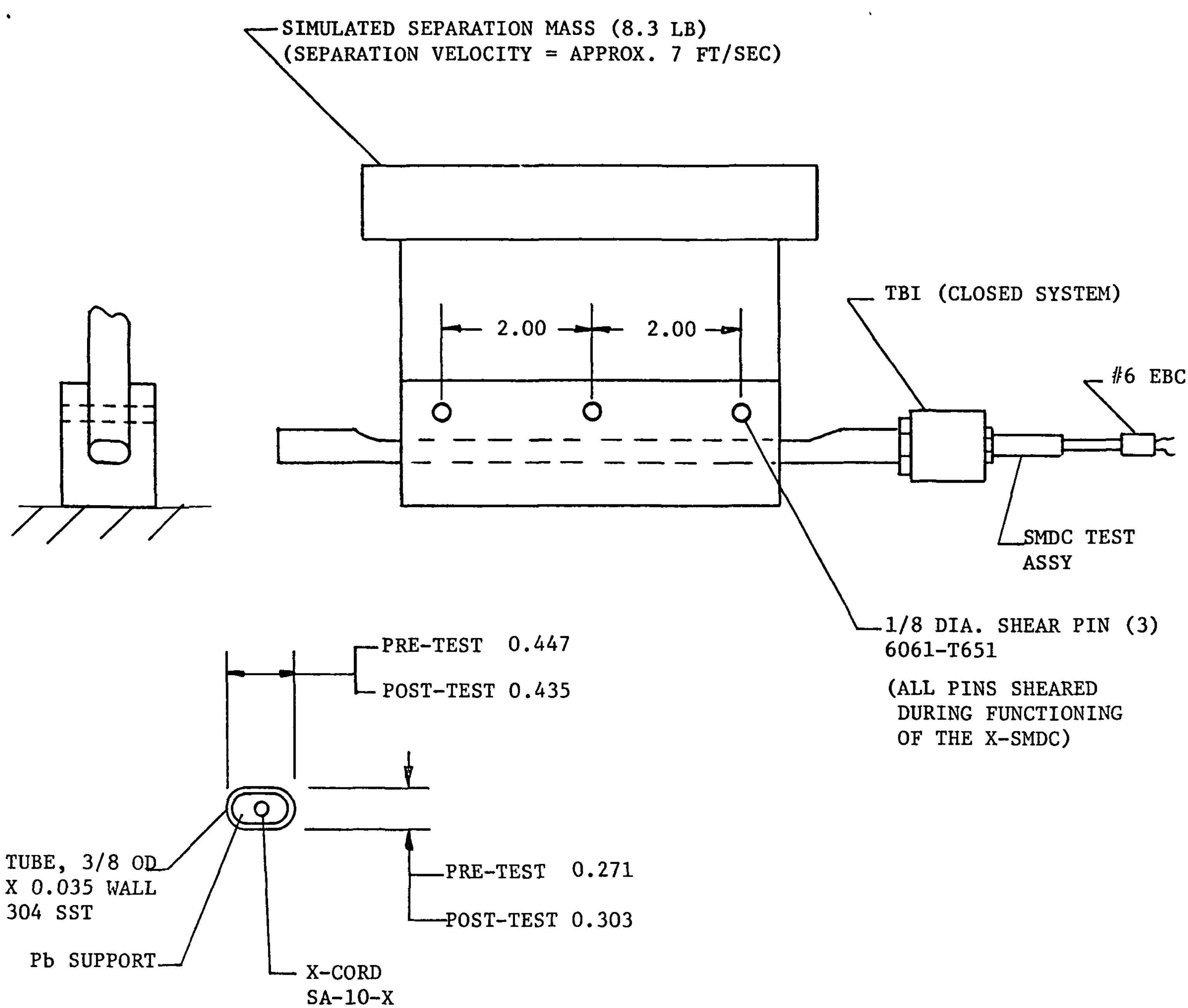
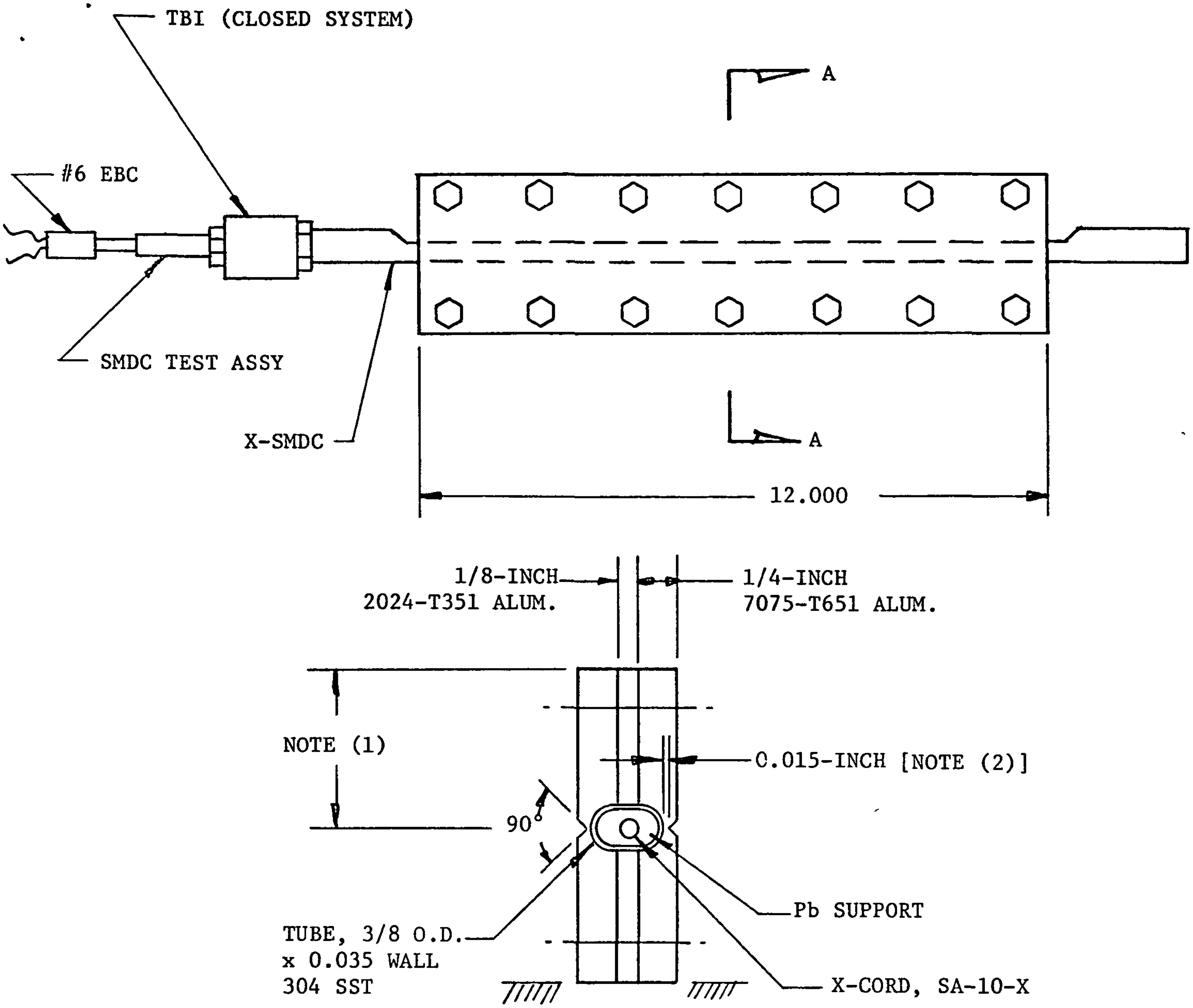


Figure B-1. X-SMDC Shear Pin Separation Application



NOTES:

(1) Weight of separated mass = 1.25 pounds. Separation velocity = 27 feet per second.

(2) Static tensile strength of joint assembly = 1350 pounds per linear inch.

(3) No ruptures were encountered.

Figure B-2. Structural Joint Separation Application

APPENDIX C - DATA FROM OTHER ET PROGRAMS

There have been numerous independent test firings of expanding tube systems at Explosive Technology. They have incorporated a variety of tube sizes, X-Cord configurations and various X-Cord support materials. The results of these tests are tabulated in Table C-I and Table C-II.

TABLE C-I. - MISCELLANEOUS TESTS USING HNS-II EXPLOSIVE CORE

TEST FIG.	TUBE SIZE (IN.)		TUBE MATERIAL		X-CORD		TUBE SUPPORT (1)				TEST TEMP. (°F)	POST FIRE DIM. (IN.)	ENERGY OUTPUT (IN.-LB)	TUBE COND.	
	OD	WALL	ALUM.	SST	TYPE	CORE LOAD (GR/FT)	FG	Si	Pb	Al				OK	RUP.
1	3/8	0.016		304	SA	6.5	X				Amb	0.278	6.38	X	
	3/8	0.020		304	SA	7.75	X				Amb	0.281	7.56	X	
	3/8	0.028		304	SA	10.0	X				Amb	0.287	11.66	X	
	3/8	0.035		304	SA	12.0	X				Amb	0.295	6.38	X	
	3/8	0.049		304	SA	12.0	X				Amb	0.280	4.40	X	
	1/4	0.028		304	SA	7.0			X		Amb	0.206	38.80	X	
	1/4	0.028		304	SA	9.0			X		Amb	0.197	58.30	X	
	1/4	0.035		304	SA	7.0			X		Amb	0.200	30.20	X	
	1/4	0.035		304	SA	9.0			X		Amb	0.193	41.20	X	
	1/4	0.028		304	SS	7.0		X			Amb	0.197	8.80	X	
	1/4	0.049		304	SA	3.5		X			Amb	0.191	3.1	X	
	1/4	0.028		304	SA	5.0		X			Amb	0.190	8.0	X	
	1/4	0.035		304	SA	7.0		X			Amb	0.209	13.3	X	
	5/16	0.028		304	SA	7.75	Teflon Ext				Amb	0.233	15.1	X	
	5/16	0.016		304	SA	5.0	Teflon Ext				Amb	0.230	10.0	X	
	5/16	0.020		304	SA	6.5	Teflon Ext				Amb	0.242	13.75	X	
	5/16	0.035		304	SA	10.0	Teflon Ext				Amb	0.245	15.0	X	
(2)	3/8	0.035		304	SA	10.0			X		Amb	0.286	48.8	X	
	3/8	0.035		304	SA	10.0		X			Amb	0.318	53.0	X	
	3/8	0.049		304	SA	10.0			X		Amb	0.287	79.3	X	
	3/8	0.049		304	SA	10.0			X		Amb	0.289	83.7	X	
	3/8	0.049		304	SA	15.0			X		Amb	0.294	146.5	X	
	3/8	0.049		304	SA	15.0			X		Amb	0.294	133.8	X	
	3/8	0.049		304	SA	19.0			X		Amb	0.297	176.5		X
	3/8	0.049		304	SA	19.0			X		Amb	0.296	181.8		X

(1) FG = Fiberglass sleeve per MIL-Y-1140 Al = 6061-T651
Si = Silicone rubber per ZZ-R-765 Pb = lead 6% antimony

(2) Same configuration as described in Appendix B.

TABLE C-II. - MISCELLANEOUS TESTS USING HNS/TI/$KClO_4$ EXPLOSIVE CORE

TEST FIG.	TUBE SIZE (IN.)		TUBE MATERIAL		X-CORD		TUBE SUPPORT				TEST TEMP. (°F)	POST FIRE [illegible]M. (IN.)	ENERGY OUTPUT (IN.-LB)	TUBE COND.	
	OD	WALL	ALUM.	SST	TYPE	CORE LOAD (GR/FT)	FG	Si	Pb	Al				OK	RUP.
1	1/4	0.028		304	STA	8.0			X		Amb	0.210	66.5	X	
	1/4	0.028		304	STA	12.0			X		Amb	∿	103.0		X
	5/16	0.035		304	STA	17.7	X				Amb	0.249	20.1	X	
	5/16	0.020		304	STA	14.0					Amb	0.249	18.0	X	
	5/16	0.016		304	STA	12.0					Amb		13.9		X
	5/16	0.028		304	STA	16.0					Amb	0.254	19.4	X	
	5/16	0.020		304	STA	16.0					Amb	∿	47.6		X
	5/16	0.020		304	STA	12.0					Amb	0.250	15.9	X	
	5/16	0.028		304	STA	14.0					Amb	0.251	18.5	X	
	5/16	0.028		304	STA	18.0					Amb	∿	48.1		X
	5/16	0.016		304	STA	8.0					Amb	0.244	3.5	X	
	5/16	0.016		304	STA	10.0					Amb	0.246	6.5	X	
	5/16	0.016		304	STA	12.0					Amb	∿	18.5		X
	5/16	0.020		304	STA	8.0					Amb	0.246	5.6	X	
	5/16	0.020		304	STA	10.0					Amb	0.249	7.5	X	
	5/16	0.020		304	STA	12.0					Amb	∿	18.5		X
	5/16	0.028		304	STA	8.0	(2 layers of fiberglass sleeving)				Amb	0.244	4.0	X	
	5/16	0.028		304	STA	10.0					Amb	0.248	9.0	X	
	5/16	0.028		304	STA	12.0					Amb	0.250	17.1	X	
	5/16	0.028		304	STA	14.0					Amb	0.257	21.5	X	
	5/16	0.035		304	STA	8.0					Amb	0.243	3.0	X	
	5/16	0.035		304	STA	12.0					Amb	0.251	9.8	X	
	5/16	0.035		304	STA	14.0					Amb	0.253	13.0	X	
	1/2	0.016		304	STA	12.0					Amb	0.387	6.5	X	
	1/2	0.016		304	STA	14.0					Amb	0.390	8.5	X	
	1/2	0.016		304	STA	18.0					Amb	∿	17.1		X
	1/2	0.020		304	STA	14.0					Amb	0.390	8.3	X	
	1/2	0.020		304	STA	18.0					Amb	0.397	14.6	X	
	1/2	0.028		304	STA	14.0					Amb	0.391	8.6	X	
	1/2	0.028		304	STA	18.0					Amb	0.395	13.6	X	
	1/2	0.028		304	STA	20.0	X				Amb	∿	18.5		X
	3/8	0.035		304	STA	20.0	X				Amb	0.288	27.1	X	
	3/8	0.035		304	STA	22.0	X				Amb	∿	32.4		X
	3/8	0.035		304	STA	24.0	4				Amb	∿	50.1		X
	3/8	0.049		304	STA	24.0	5				Amb	0.297	44.6	X	

TABLE C-II. - MISCELLANEOUS TESTS USING HNS/TI/$KClO_4$ EXPLOSIVE CORE (Concluded)

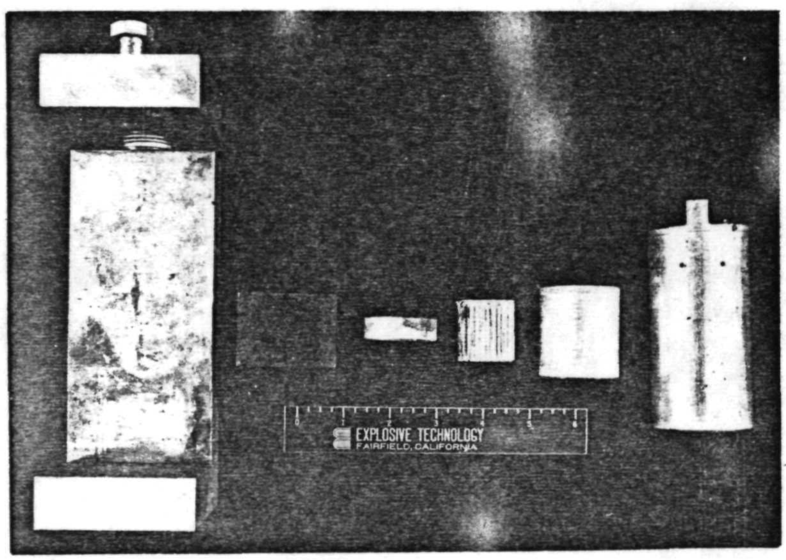
TEST FIG.	TUBE SIZE (IN.) OD	WALL	TUBE MATERIAL ALUM.	SST	X-CORD TYPE	CORE LOAD (GR/FT)	TUBE SUPPORT FG	Si	Pb	Al	TEST TEMP. (°F)	POST FIRE DIM. (IN.)	ENERGY OUTPUT (IN.-LB)	TUBE COND. OK	RUP.
1	3/8	0.028		304	STA	18.0	4				Amb	0.298	26.1	X	
	3/8	0.049		304	STA	24.0	5				Amb	0.300	38.3	X	
	3/8	0.049		304	STA	28.0	5				Amb	0.306	56.8	X	
	3/8	0.049		304	STA	32.6	5				Amb	0.318	62.7	X	
	3/8	0.016		304	STA	8.0	X				Amb	0.282	4.0	X	
	3/8	0.016		304	STA	10.0	X				Amb	0.284	9.5	X	
	3/8	0.016		304	STA	12.0	X				Amb	0.292	16.3	X	
	3/8	0.016		304	STA	14.0	X				Amb	0.297	21.7	X	
	3/8	0.020		304	STA	8.0	X				Amb	0.286	3.4	X	
	3/8	0.020		304	STA	10.0					Amb	0.288	6.1	X	
	3/8	0.020		304	STA	12.0					Amb	0.290	18.1	X	
	3/8	0.020		304	STA	14.0					Amb	--	27.0		X
	3/8	0.028		304	STA	12.0					Amb	0.287	17.6	X	
	3/8	0.028		304	STA	14.0					Amb	0.290	21.6	X	
	3/8	0.028		304	STA	16.0					Amb	0.297	25.1	X	
	3/8	0.028		304	STA	18.0					Amb	0.300	31.0	X	
	3/8	0.035		304	STA	12.0					Amb	0.286	13.4	X	
	3/8	0.035		304	STA	14.0					Amb	0.287	13.8	X	
	3/8	0.035		304	STA	16.0					Amb	0.288	17.9	X	
	3/8	0.035		304	STA	18.0					Amb	0.289	23.4	X	
	3/8	0.049		304	STA	14.0					Amb	0.282	14.5	X	
	3/8	0.049		304	STA	16.0					Amb	0.288	15.9	X	
	3/8	0.049		304	STA	18.0					Amb	0.289	19.0	X	
	3/8	0.049		304	STA	20.0					Amb	0.290	21.8	X	
	3/8	0.035		304	STA	20.0					Amb	0.290	26.4	X	
	3/8	0.035		304	STA	22.0	X (2 layers of fiberglass sleeving)				Amb	--	30.8		X
	3/8	0.049		304	STA	22.0	X				Amb	0.286	31.9	X	
	3/8	0.049		304	STA	24.0	X				Amb	0.287	39.7	X	
	3/8	0.049		304	STA	14.0			X		Amb	0.295	163.3	X	
	3/8	0.049		304	STA	14.0			X		Amb	0.295	154.5	X	
	3/8	0.049		304	STA	16.0			X		Amb	0.295	152.4	X	
	3/8	0.049		304	STA	16.0			X		Amb	0.295	149.4	X	
	3/8	0.049		304	STA	18.0			X		Amb	0.299	203.8	X	
	3/8	0.049		304	STA	18.0			X		Amb	0.299	191.4	X	

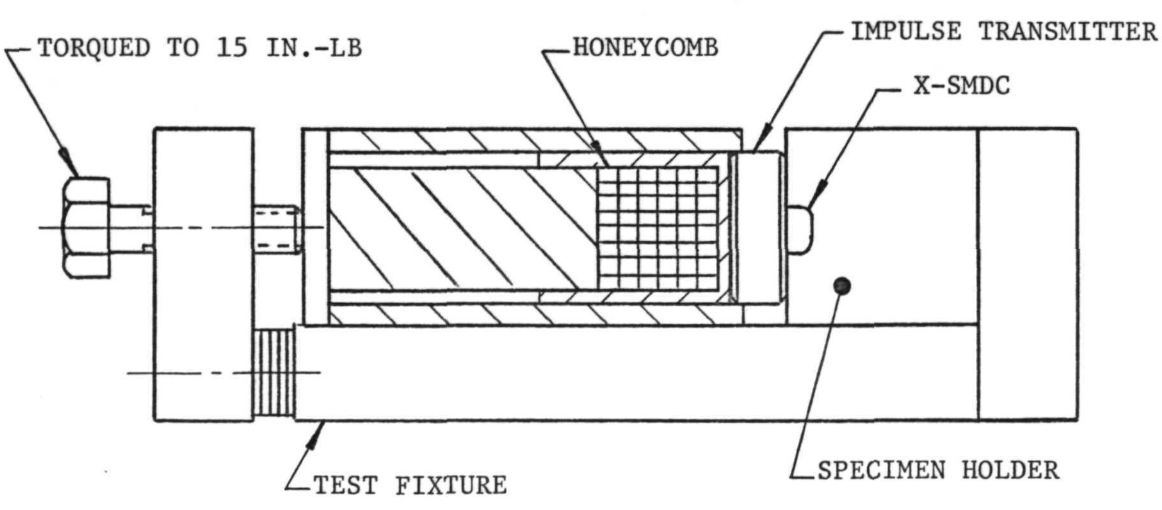
APPENDIX D - ENERGY SENSOR OPERATION

For the uninitiated reader, a description of the energy sensor test setup is in order. First, to provide a relative comparison of energy output between different configurations and size of tubes, and in fact between tubes of the same type, a test setup using a known "energy sensing" value is necessary.

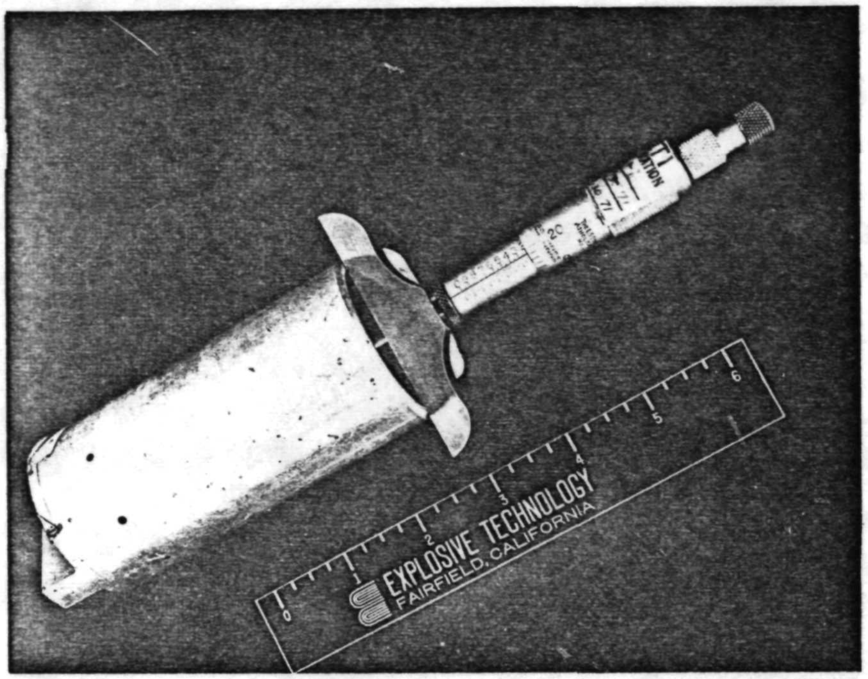
This known value is provided by a square piece of honeycomb aluminum which is pretested for strength. Explosive Technology calibrates each honeycomb square in a Tinius Olsen Tension/Compression Tester. The honeycomb is precrushed approximately 0.100-inch to determine its strength in pounds of force.

The honeycomb square is then placed in the test setup as shown below.

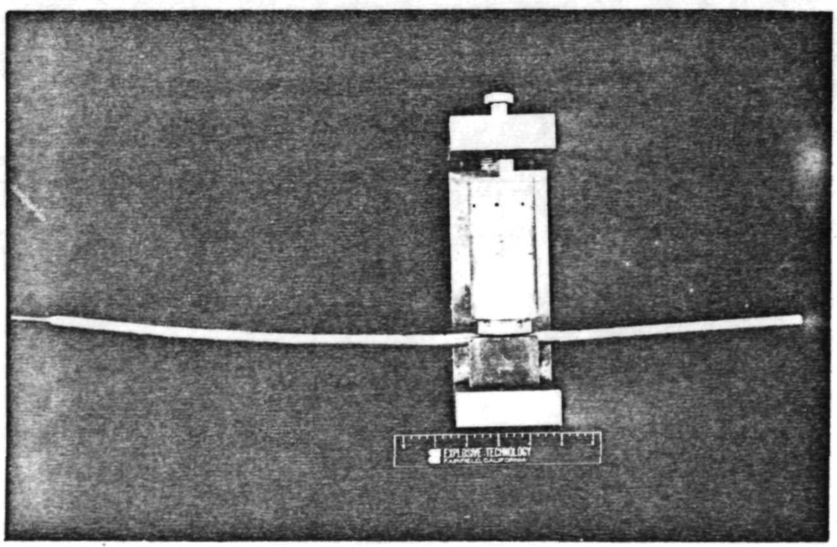




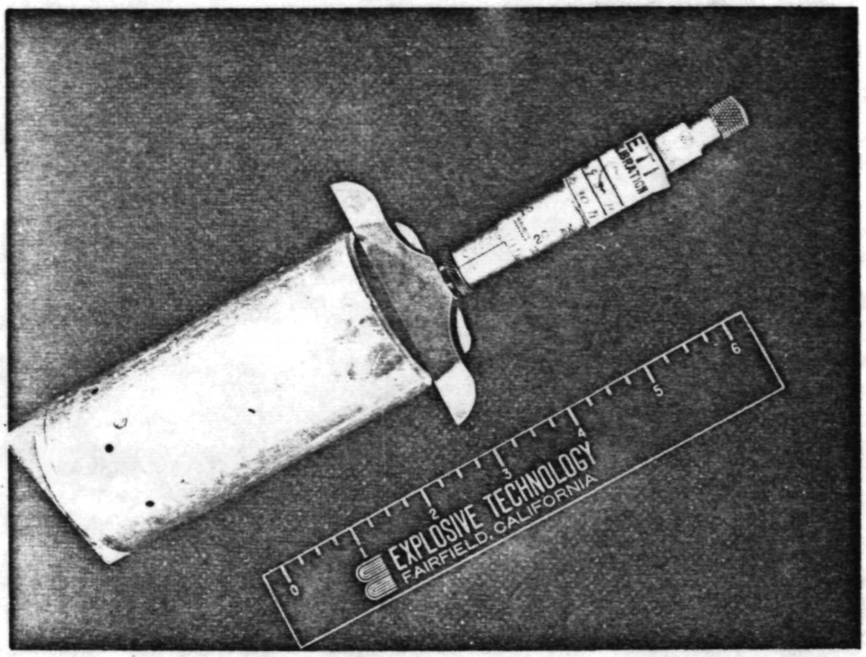
A pre-fire measurement is made to determine the initial distance to the inside piston, which covers the honeycomb square.



The expanding tube is placed in the energy sensor apparatus. A torque of 15 inch-pounds is applied to the set screw on the holding block to ensure intimate contact of all components.

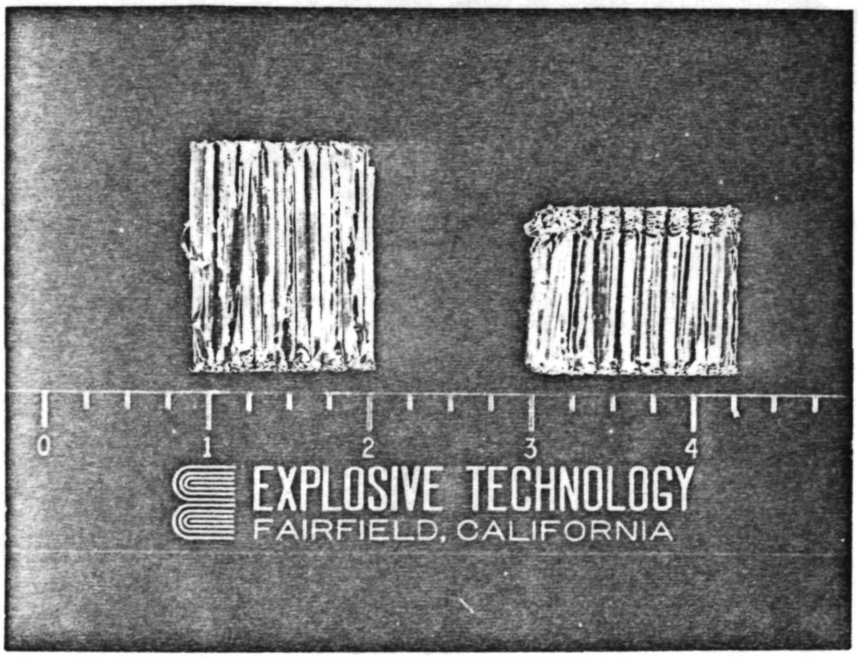


The expanding tube is fired, the setup disassembled, and a post-fire measurement of honeycomb crush is made.



The difference between pre-fire and post-fire measurements is multiplied by the strength value of the honeycomb square, previously tested. This calculation is $(X - Y) K = E$, where X is the pre-fire measurement in inches, Y is the post-fire measurement in inches, K is the strength of the honeycomb square in inch-pounds, and E is the energy output in inch-pounds per inch.

A typical piece of honeycomb before and after a test is shown below.



REFERENCES

1. Bement, L. J.: Application of Temperature Resistant Explosives to NASA Missions. NASA-Langley Res. Center, June 1970.
2. Bement, L. J.: Monitoring of Explosive/Pyrotechnic Performance. Presented at the Seventh Symposium on Explosives and Pyrotechnics, Philadelphia, Pennsylvania, September 8-9, 1971.
3. Anon: ASME Metals Handbook. Vol. 1 - Properties and Selection of Metals. Vol. 4 - Metal Forming. Eighth ed., 1969.
4. Berman, I., et al: Development and Use of Explosive Forming for Commercial Applications. Int. Conf. for High-Energy Forming. Univ. of Denver, June 1967.
5. Braun, W. H.: High-Performance Tubing. Machine Design, October 15, 1970.
6. Butcher, B. M.; Karnes, C. M.: Strain-Rate Effects in Metals. J. of Appl. Phys., January 1966. p. 402.
7. Clark, D. S.; Wood, D. S.: The Tensile Impact Properties of Some Metals and Alloys. Calif. Inst. of Tech., Pasadena, February 1949.
8. Duvall, G. E.; Fowles, G. R.: Shockwaves, High Pressure Physics and Chemistry 2. ch. 9. Academic Press, 1963.
9. Gluckman, I. B.: Evolution of Linear Separation Systems for Missile and Space Applications. Sixth Symposium of Electro-Explosive Devices. San Francisco, 1969.
10. Goforth, R. E.: Criteria for Formability, High-Velocity Forming of Metals. ch. 8. Prentice-Hall, 1964.
11. Hogatt, C. R.; Orr, W. R.; Recht, R. F.: The Use of an Expanding Ring for Determining Tensile Stress-Strain Relationships as Functions of Strain Rate. Int. Conf. for High-Energy Forming. Univ. of Denver, June 1970.
12. Kawata, K., et al: Some Analytical and Experimental Investigations On High Velocity Elongation Of Sheet Metals by Tensile Shock. Behavior of Dense Media Under High Dynamic Pressures. Symp. H. D. P. Paris. September 1967. Gordon and Breach, 1968.
13. Kumar, A., et al: Survey of Strain-Rate Effects. Int. Conf. for High-Energy Forming. Univ. of Denver, June 1967.
14. Metallurgical Society Conf., Colorado: Response of Metals to High Velocity Deformation. Interscience Publishers, 1961.
15. Noland, M. C., et al: High-Velocity Metalworking - A Survey. NASA Report SP-5062, 1967.
16. Orava, R. N.: The Effect of Dynamic Strain Rates on Room Temperature Ductility. Int. Conf. for High Energy Forming, Univ. of Denver, June 1967.
17. Perrone, N.: On a Simplified Method for Solving Impulsively Loaded Structures of Rate - Sensitive Materials. J. Appl. Phys., September 1965.
18. Rinehart, J. S.; Pearson, J.: Explosive Working of Metals. Pergamon Press, 1963.
19. Roth, J.: Deformation of Sheet Metal and Metal Tubes by Explosives. Trans. Quart., December 1963.
20. Schimmel, M. L.; Drexelius, V. W.: Measurement of Explosive Output. Proc. of 5th Ann. Symp. of EED's, Franklin Inst., June 1967.
21. Smith, C. S.: Metallographic Studies of Metals After Explosives Shock. Trans. of Metall. Soc. of AIME, October 1958. p. 574.
22. Tennyson, R. C.: Application of High Speed Photography to the Photoelastic Analysis of Structural Stability Problems. S.P.I.E. Journal, July 1970.

23. Wilde, A. F., et al: Dynamic Birefringence and Strain Produced in Two Transparent Polymers by Mechanical Impact. The Rheology of Solids, Interscience, 1967.
24. Otto, H. E.; Mikesell, R.: The Shock-Hardening of Structural Metals. Int. Conf. for High-Energy Forming, Univ. of Denver, June 1967.
25. Youngdahl, C. K.: The Dynamic Plastic Response of a Tube to an Impulsive Ring Load of Arbitrary Pulse Shape. Argonne National Lab. Report ANL-7562, April 1969.